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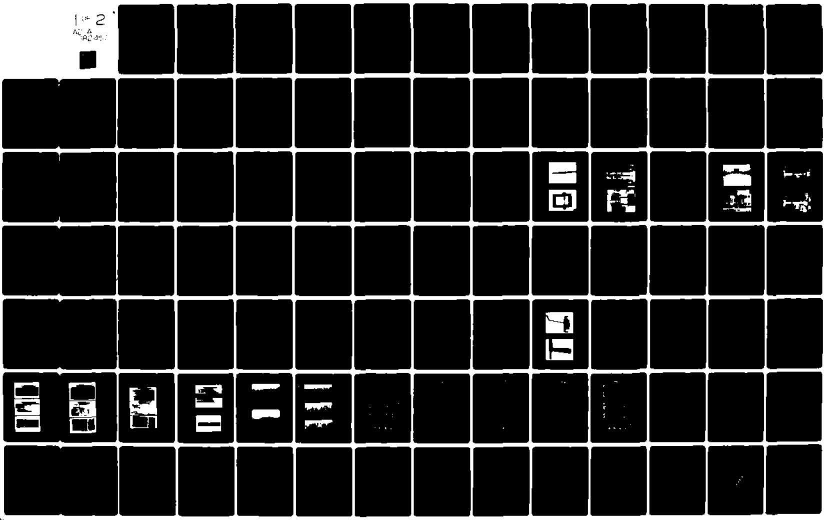

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INVESTIGATION OF THE MECHANICAL AND
CORROSION PROPERTIES OF MA 87 ALUMINUM POWDER ALLOY

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Structures and Materials
LOCKHEED-CALIFORNIA COMPANY
Burbank, California

FINAL REPORT
Contract N62269-78-C-0446

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Prepared for
NAVAL AIR DEVELOPMENT CENTER
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Warminster, Pennsylvania 18974

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Compression	Exfoliation	Fatigue Crack Growth
		Aluminum Powder Alloy

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Mechanical, corrosion and fracture properties were determined for two MA87(CT91)-T7E69 powder alloy extruded shapes. Four lots of material were extruded and heat treated in production facilities. Mechanical properties including tensile, compression, shear and bearing were comparable to available data for 7075-T6 extrusions. The MA87(CT91)-T7E69 extrusions were resistant to exfoliation when exposed to EXCO, salt spray, or sea coast environments, although pitting was observed. Stress corrosion

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20. ABSTRACT (Continued)

failures in the alternate immersion test resulted from pitting and not intergranular cracking. Constant amplitude fatigue behavior of K_t = 2.7 and 4.0 specimens were significantly better than the standard design allowables used for 7075-T6 extrusions. In addition, the P-3 spectrum fatigue results for MA87(CT91)-T7E69 were better than previous results obtained for 7075-T6510 and 7050-T7E73 extrusions; however, a high scatter factor was evident for the MA87(CT91) material. Fatigue crack growth and fracture toughness behavior were similar to available data for 7075-T6 and T76 extrusions. The evaluation of MA87(CT91)-T7E69 production extrusions revealed a combination of properties which warrants the continued development of the material.

PREFACE

This investigation was conducted by Lockheed-California Company, Burbank, California, for the Department of the Navy, Naval Air System Command/Naval Air Development Center under NADC Contract N62269-78-C-0446. Technical monitors for the Navy were E. Balmuth and R. Steskal of NASC, and S. Ketchum and A. Fletcher of NADC. Contracting officer for NADC was S.J. Barber. This report covers the work performed from September 1978 to December 1979.

The authors are grateful for the contributions of S. T. Chiu, A. Chulick, C. T. Clark, J. Cox, J. Ekvall, W. Leuders, D. E. Pettit, W. Renslen, and J. M. Van Orden.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

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INTRODUCTION

High strength aluminum alloys offer significant design, cost, and manufacturing advantages over other materials for airframe construction. One of the new aluminum alloys is MA87, currently designated CT91, which is produced by powder metallurgy techniques. Extrusions made from this material at Alcoa's research facility have shown comparable strength, higher corrosion resistance, and improved fatigue behavior when compared with 7075-T6 extrusion properties. When the properties of MA87 (CT91) were included in a Lockheed-California Company weight payoff study for a potential NAVY V/STOL aircraft, the study showed a 6% weight saving in overall structural weight could be achieved by replacing existing ingot aluminum alloys. The improved properties and potential weight saving make the continued development of MA87 (CT91) attractive. This investigation was initiated to establish the MA87 (CT91) payoffs available for existing and proposed Navy Aircraft and to accelerate its production availability. Specific objectives were to verify that the reported properties of MA87 (CT91) extrusions can be reproduced under mill production conditions, and to establish a data base for preliminary design allowables.

Data generated from this and other government-funded programs will provide a basis for the structural evaluation of MA87 (CT91) for current or future Navy aircraft applications.

MATERIAL

For this program, two specific extruded shapes were selected by Lockheed-California Company. One shape, Wing Spar Cap, LS9788, shown in figure 1, was selected because it is used for the P-3 aircraft and had been used to evaluate 7075-T6510 and 7050-T7E73 material in a previous NADC funded program (reference 1); therefore, several direct comparisons could be made. The other shape, Flanged Cap, LS13116, shown in figure 2 was selected to provide a shape having both a heavy base section thickness of 1.07 inch and a thin flange section thickness of 0.15 to 0.25 inch in the same extrusion. This would permit the evaluation of both thick and thin sections processed under the same conditions. To expedite the program, the MA87 (CT91) production extrusions were ordered by NADC to the following requirements negotiated between Lockheed-California Company and Alcoa.

- Composition: Per Alcoa Internal Quality Control. Actual composition to be reported.

- Quantity:

	Total Length
LS9788 (Figure 1)	
Heat Treat Lot 1A1	20 ft.
Heat Treat Lot 1A2	20 ft.
LS13116 (Figure 2)	
Heat Treat Lot 2A1	20 ft.
Heat Treat Lot 2A2	20 ft.
Total	80 ft.

- Process and QA requirements shall be in accordance with the following.

  - Powder atomization and processing shall be in accordance with Alcoa's latest practice aimed at providing the best combination of strength, corrosion resistance, toughness, and fatigue.

  - Extrusion shall be performed on production extrusion equipment.

- The extrusions shall be solution heat treated for 2 hours at 910°F, stretched, and aged 24 hours at 250°F plus 4 hours at 325°F to the -T7E69 temper in production facilities to achieve the following target minimum properties:

Tensile Strength	(longitudinal)	82 ksi
Yield Strength	(longitudinal)	76 ksi
Elongation	(longitudinal)	7%
Stress Corrosion Resistance		45 ksi
Exfoliation Resistance		E-B or better per EXCO test of T/10 plane.

- Alcoa shall supply actual test results.

A total of 68 feet of extrusions were received; although this was less than requested it was a sufficient quantity to perform the evaluation.

The actual test data supplied by Alcoa are compared with the target values in table 1. Only two variations were observed, one was a minimum yield value of 0.2 ksi below the 76 ksi target value and the other was the iron (Fe) content was .01 to .02 percent higher than the target value. Both these differences were considered minor.

TABLE 1. - ALCOA TEST REPORT PROPERTIES FOR MA87(CT91)

Shape	Lot	Quantity Feet	Grain Direction	Tensile Properties Ultimate Ksi	Tensile Properties Yield Ksi	Tensile Properties Elong % in 2"
Wing Spar Cap LS9788	E89081A1 (1A1)	13	L max L min	87.4 84.4	82.3 77.6	10.0 8.5
	E89081A2 (1A2)	26	L max L min	84.6 83.9	77.9 77.2	10.5 10.5
Flanged Cap LS13116	C89082A1 (2A1)	11	L max L min	88.4 83.7	82.1 75.8	12.5 12.0
	E89082A2 (2A2)	18	L max L min	89.4 84.9	83.3 77.1	12.0 11.0
Target		–	L	82	76	7

			Composition, Percent								
			Zn	Mg	Cu	Co	Fe	Si	Ni	Be	A1
Both	All	max	6.64	2.59	1.64	.48	.12	.06	.01	.002	Bal
		min	6.30	2.40	1.49	.45	.11	.05	.01	.002	
Target			6.5	2.5	1.5	.4	.10 max	.10 max	–	–	Bal

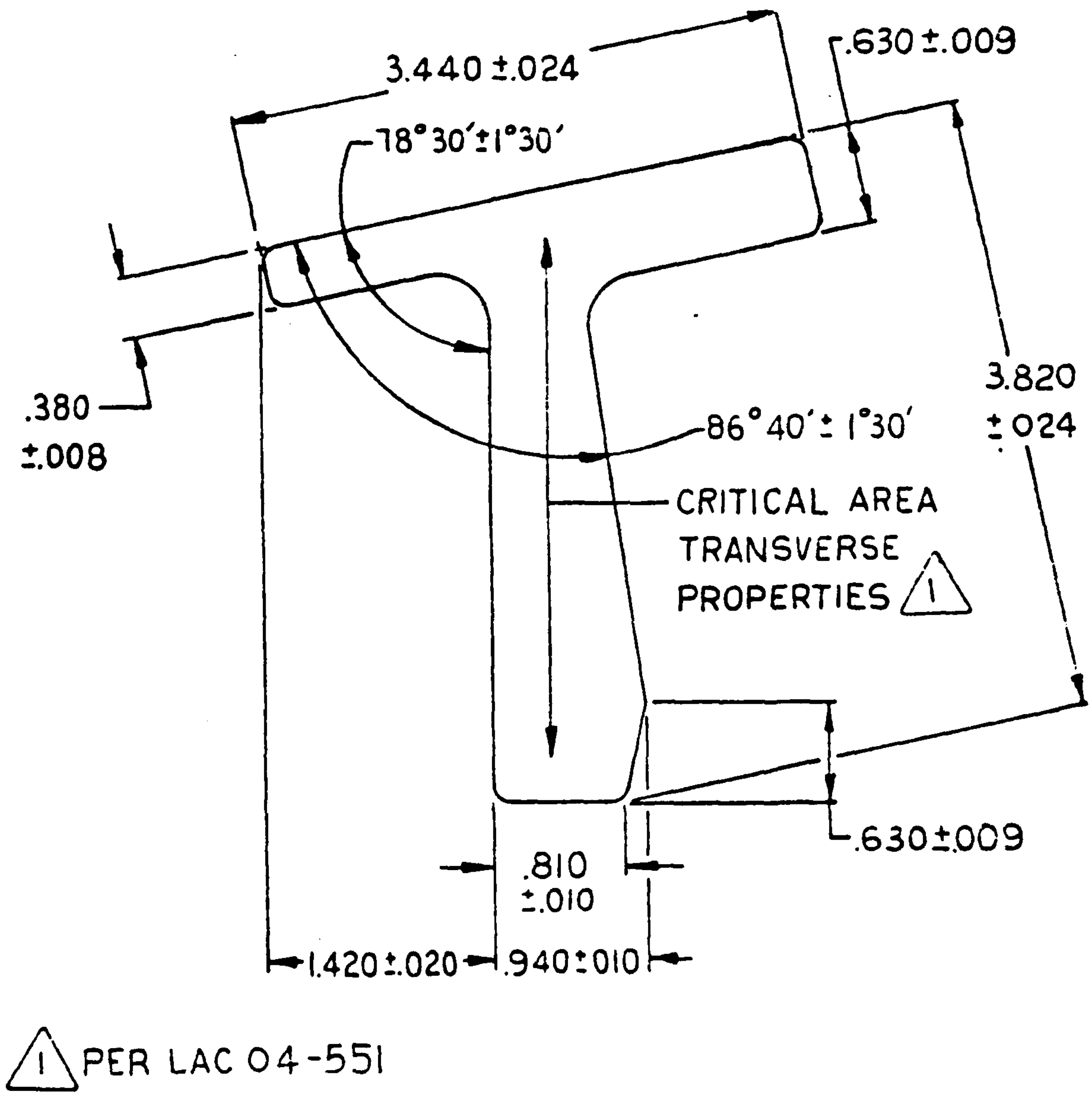


Figure 1. - Wing spar cap extrusion, LS9788.

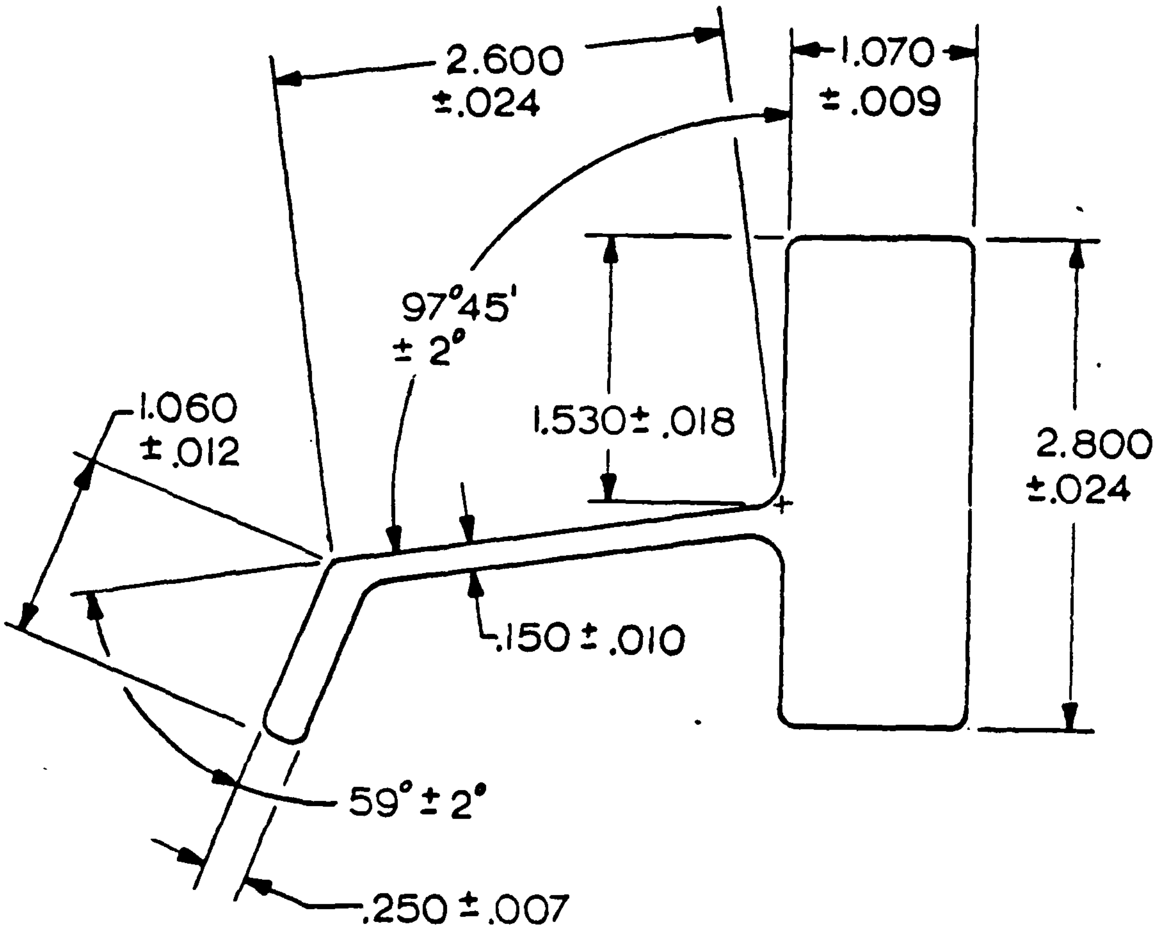


Figure 2. - Flanged cap extrusion, LS13116.

TEST SPECIMEN PREPARATION AND PROCESSING

The quantity and types of specimens tested are summarized in table 2. The specific configuration used for each test is identified by figure number in table 2. Specimen configurations are shown in figures 3 through 13. Typical locations of specimens taken from the extrusions are shown in figures 14 through 16.

The specimens conform with the applicable ASTM requirements; however, the compact tension specimen used for fatigue crack growth, figure 13, was increased in overall specimen size. This provided a longer ligament length for crack growth monitoring. The initial crack-length-to-width ratio a/w, was also reduced from that recommended in ASTM Standard E 399-74 to further increase the usable ligament length.

After machining, only the wing spar cap spectrum fatigue specimens received additional processing. These specimens were given a light alkaline etch, then chemical film treated per LAC-0498(2) which meets MIL-C-5541A. The processing was performed in Lockheed-California Company production facilities. The stress concentration notches were drilled and reamed after the chemical film treatment.

TABLE 2. - MA87(CT91) PROGRAM TESTING SUMMARY

Test	Wing Spar Cap (1)		Flanged Cap (1)				Total Specimens
			Base		Flange		
	Lot 1A1	Lot 1A2	Lot 2A1	Lot 2A2	Lot 2A1	Lot 2A2	
Tensile							
(a) Longitudinal	5-3	5-3	5-3	5-3	5-5	5-5	30
(b) Long transverse	5-3	5-3	5-3	5-3	5-6	5-6	30
(c) Short transverse	3-4	3-4	3-4	3-4	–	–	12
Compression							
(a) Longitudinal	7-7	7-7	7-7	7-7	7-7	7-7	42
(b) Long transverse	3-7	3-7	3-7	3-7	–	–	12
Shear, longitudinal	3-8	3-8	3-8	3-8	–	–	12
Bearing, longitudinal	3-9	3-9	3-9	3-9	3-9	3-9	18
Moduli, longitudinal							
(a) Tensile	5-3	5-3	5-3	5-3	5-5	5-5	30(2)
(b) Compression	7-7	7-7	7-7	7-7	7-7	7-7	42(3)
Corrosion Behavior							
1. Exfoliation							
(a) EXCO	1-10	1-10	1-10	1-10	1-10	1-10	6 (4)
(b) Salt Spray	1-10	1-10	1-10	1-10	1-10	1-10	6 (4)
(c) Sea Coast Exposure	1-10	1-10	1-10	1-10	1-10	1-10	6
2. Stress							
(a) Alternate Immersion							
25 Ksi	–	–	3-4	3-4	–	–	6 (4)
35 Ksi	–	–	3-4	3-4	–	–	6 (4)
45 Ksi			3-4	3-4			6
Fatigue							
(a) Constant Amplitude							
$K_t = 2.7$, $R = 0.1$	5-11	5-11	5-11	5-11	5-11	5-11	30
$K_t = 4.0$, $R = 0.1$	5-12	5-12	5-12	5-12	5-12	5-12	30
$K_t = 2.7$, $R = 0.5$	5-11		5-11				10
(b) Spectrum (P-3)							
$K_t = 2.7$	4-11	2-11	2-11	2-11	2-11	2-11	14
$K_t = 4.0$	4-12	2-12	2-12	2-12	2-12	2-12	14
Fracture Behavior							
(a) Crack Growth, da/dN							
L-T, Lab Air	–	–	3-13	2-13	–	–	5
L-T 3.5% Salt	–	–	2-13	2-13	–	–	4
(b) Fracture Toughness							
L-T, Lab Air	–	–	6-13	6-13	–	–	12

(1) The first digit is the number of specimens tested and the second digit is the figure number of the specimen tested; i.e., 5-3 is 5 specimens of Figure 3 configuration were tested.
(2) Data from tensile test specimens.
(3) Data from compression test specimens.
(4) Duplicate corrosion specimens were machined and sent to NADC for testing.

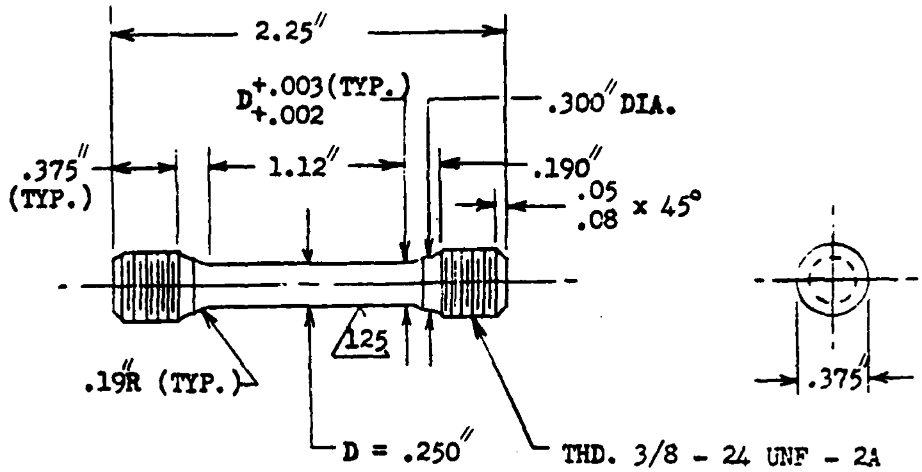


Figure 3. - Standard round tensile specimen.

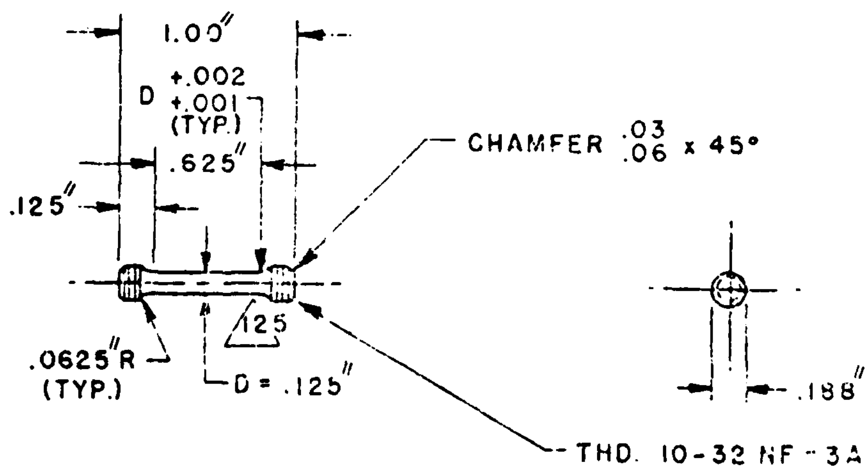


Figure 4. - Subsize round tensile specimen.

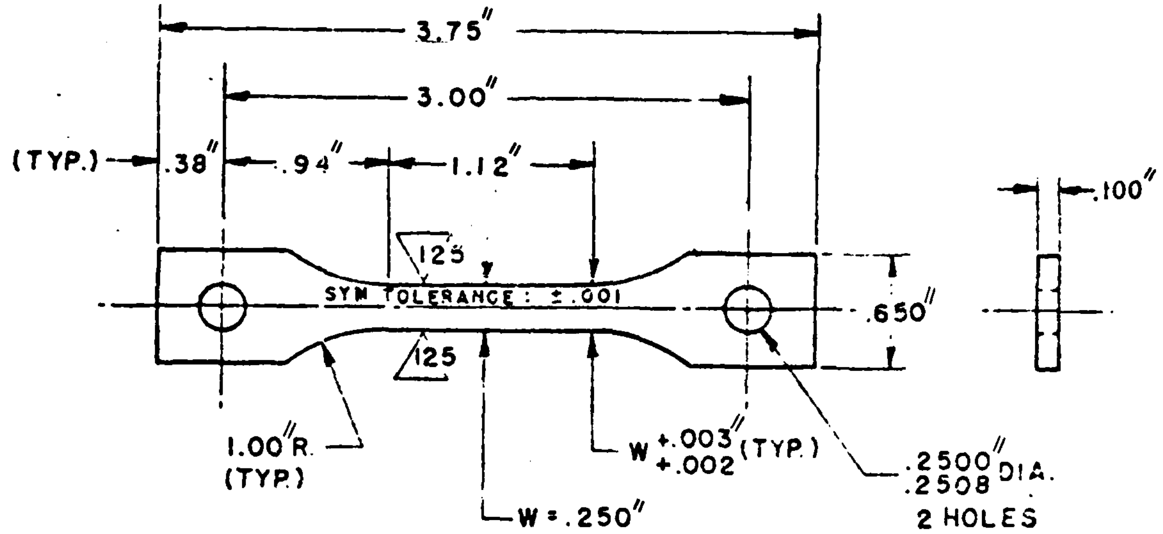


Figure 5. - Standard flat tensile specimen.

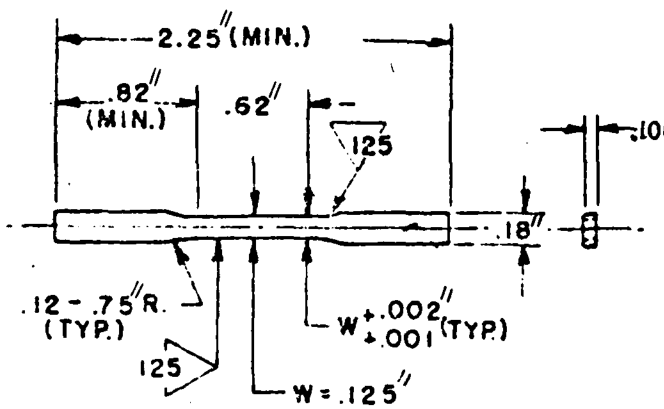


Figure 6. - Subsize flat tensile specimen.

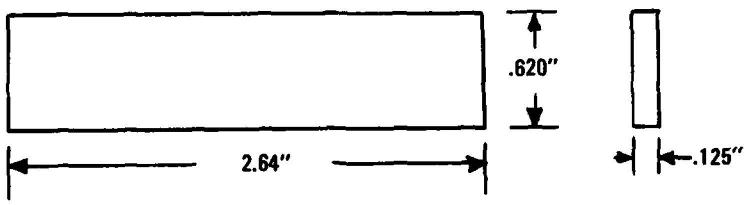


Figure 7. - Compression specimen.

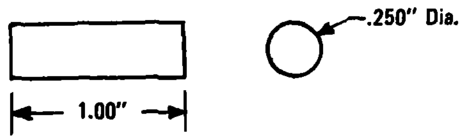


Figure 8. - Shear specimen.

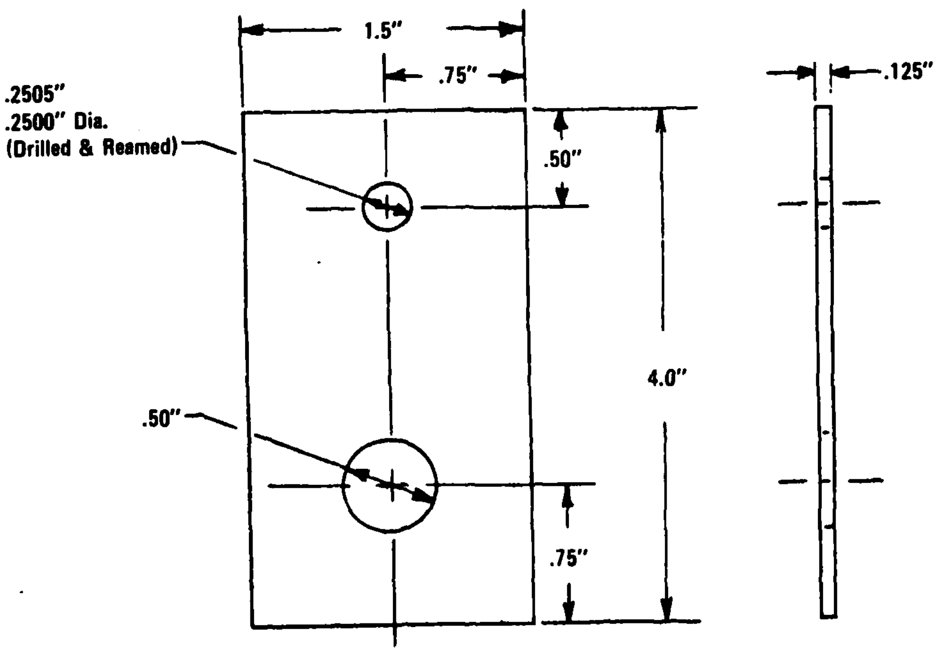


Figure 9. - Bearing specimen.

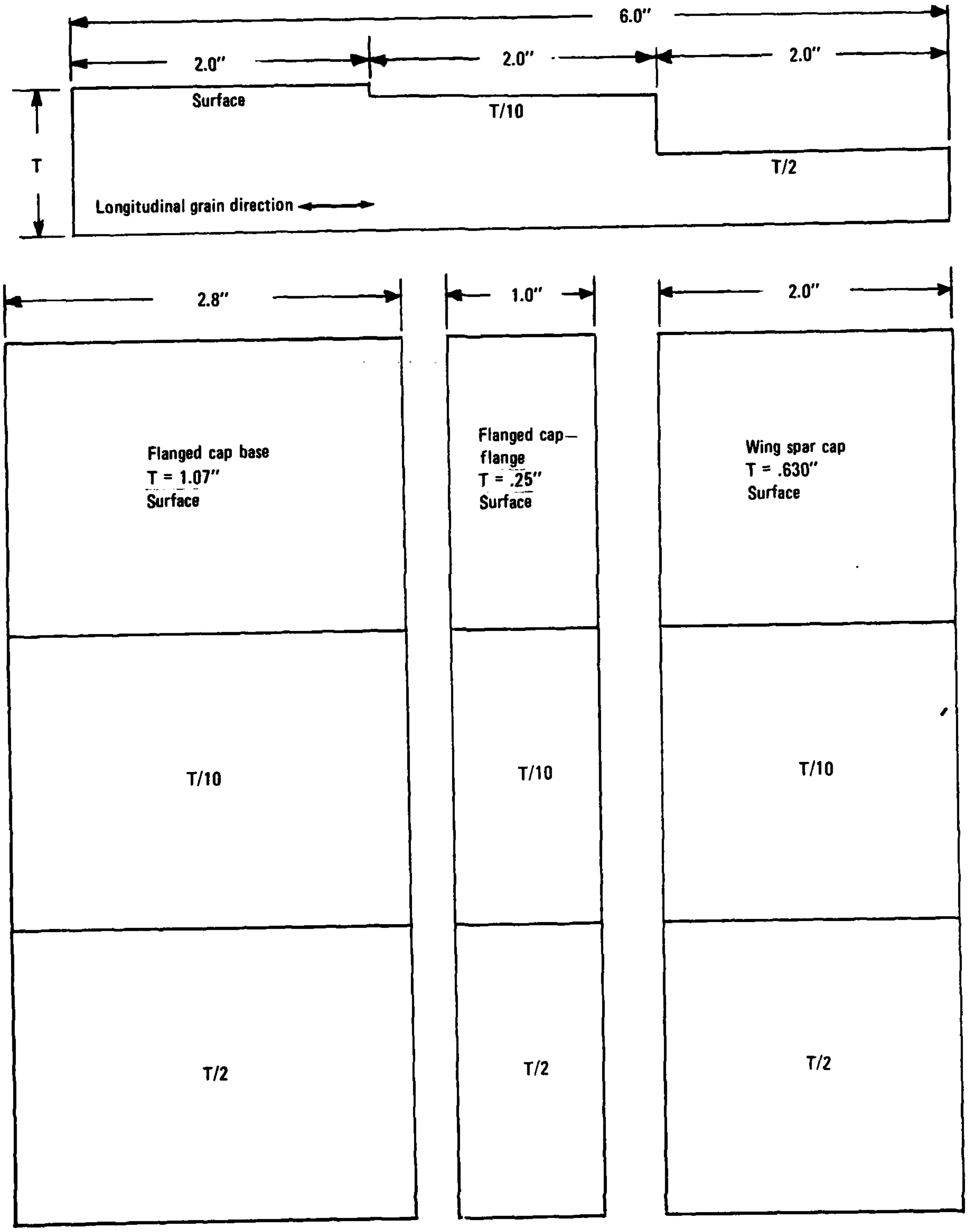


Figure 10. - Exfoliation specimens.

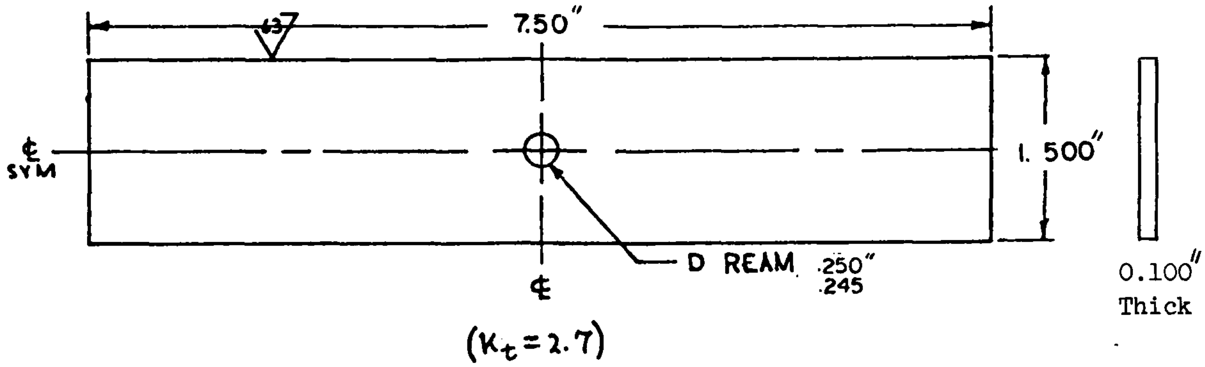


Figure 11. - Fatigue specimen, K_t = 2.7.

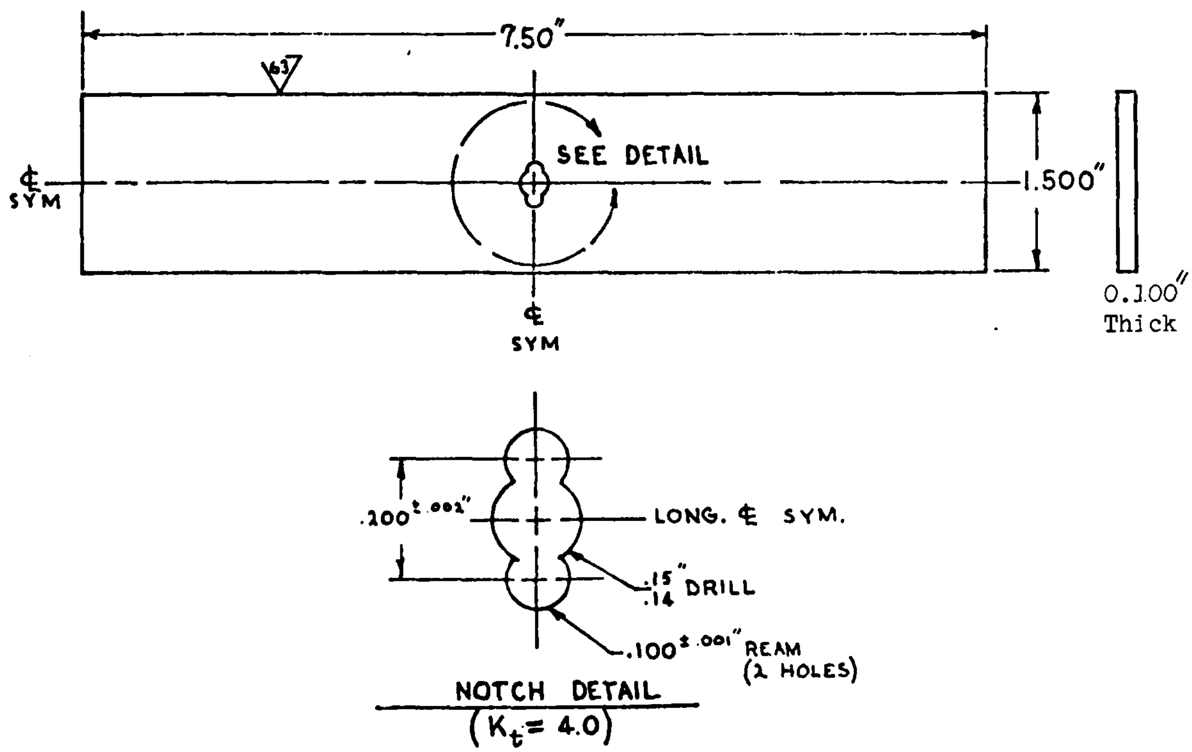
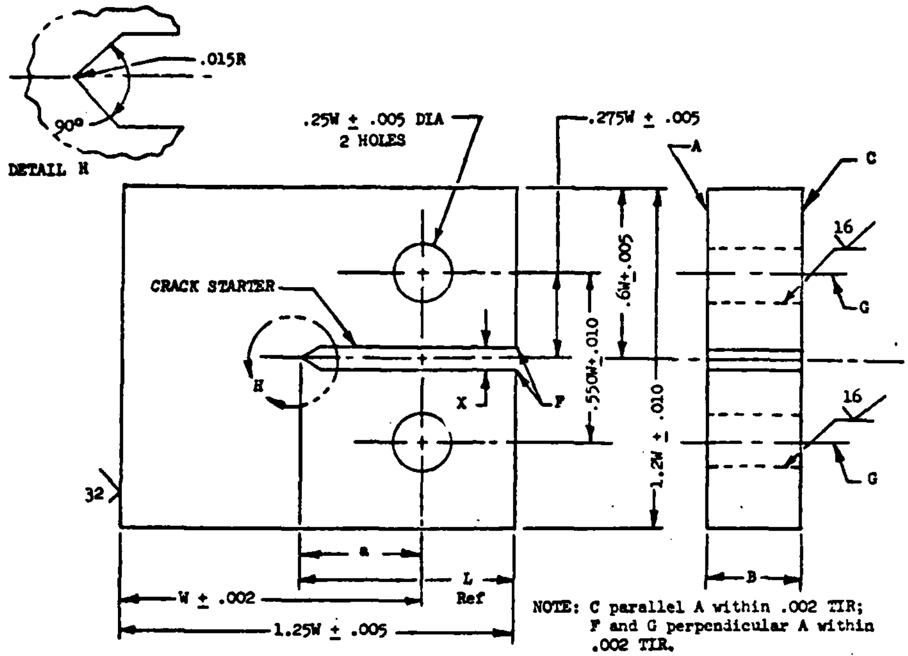


Figure 12. - Fatigue specimen, K_t = 4.0.



Symbol	Specimen Dimensions	
	Fracture Toughness inches	Fatigue Crack Growth inches
a	.696	.250
B	.750	.750
L	1.071	.800
W	1.500	2.200
.25W	.375	.550
.275W	.412	.605
.550W	.825	1.210
.6W	.900	1.320
1.2W	1.800	2.640
1.25W	1.875	2.750
X	.100	.100

Figure 13. - Fracture toughness and fatigue crack growth specimens.

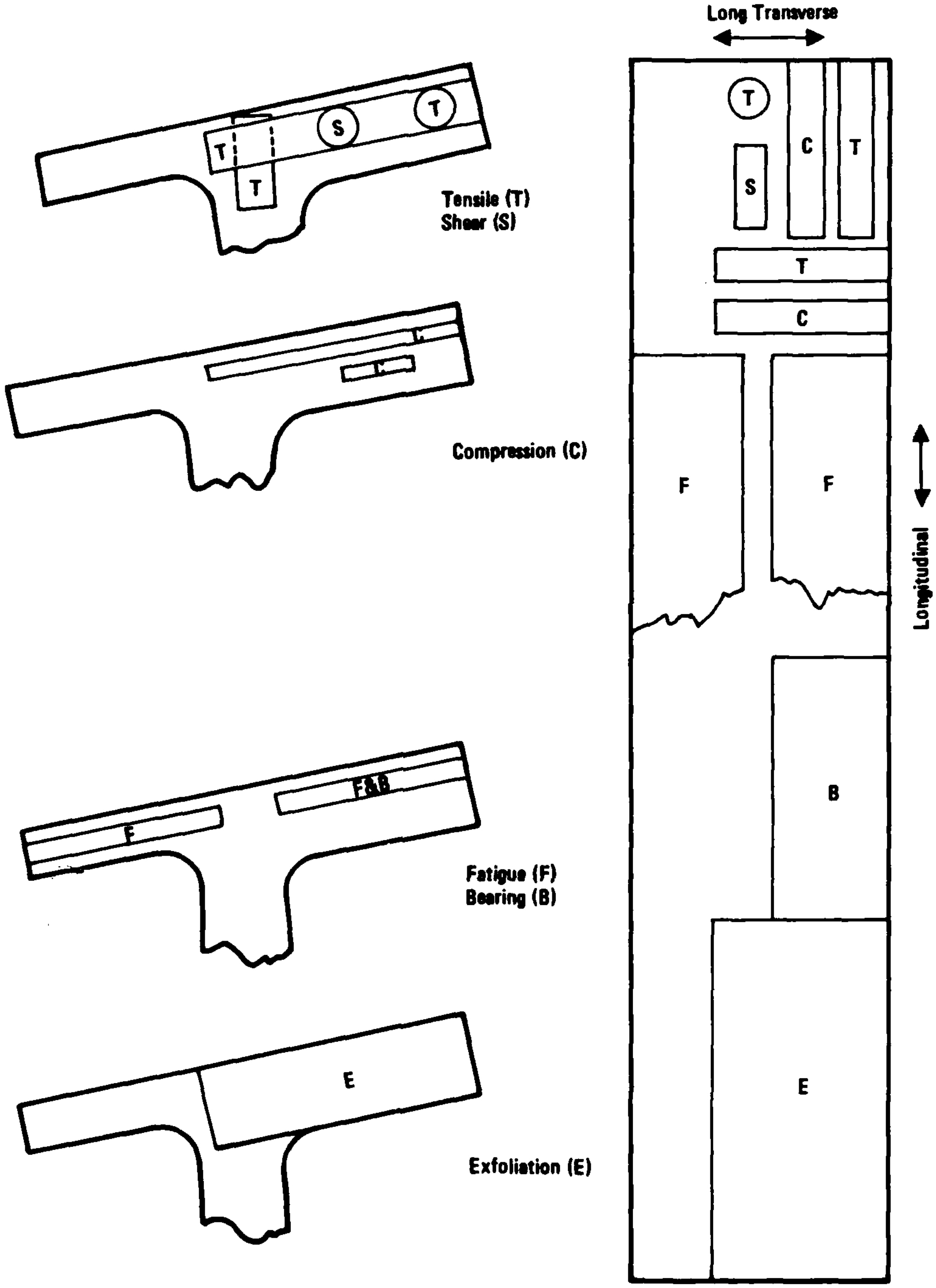


Figure 14. - Schematic of test specimen layout for wing spar cap, LS 9788. (Not to scale)

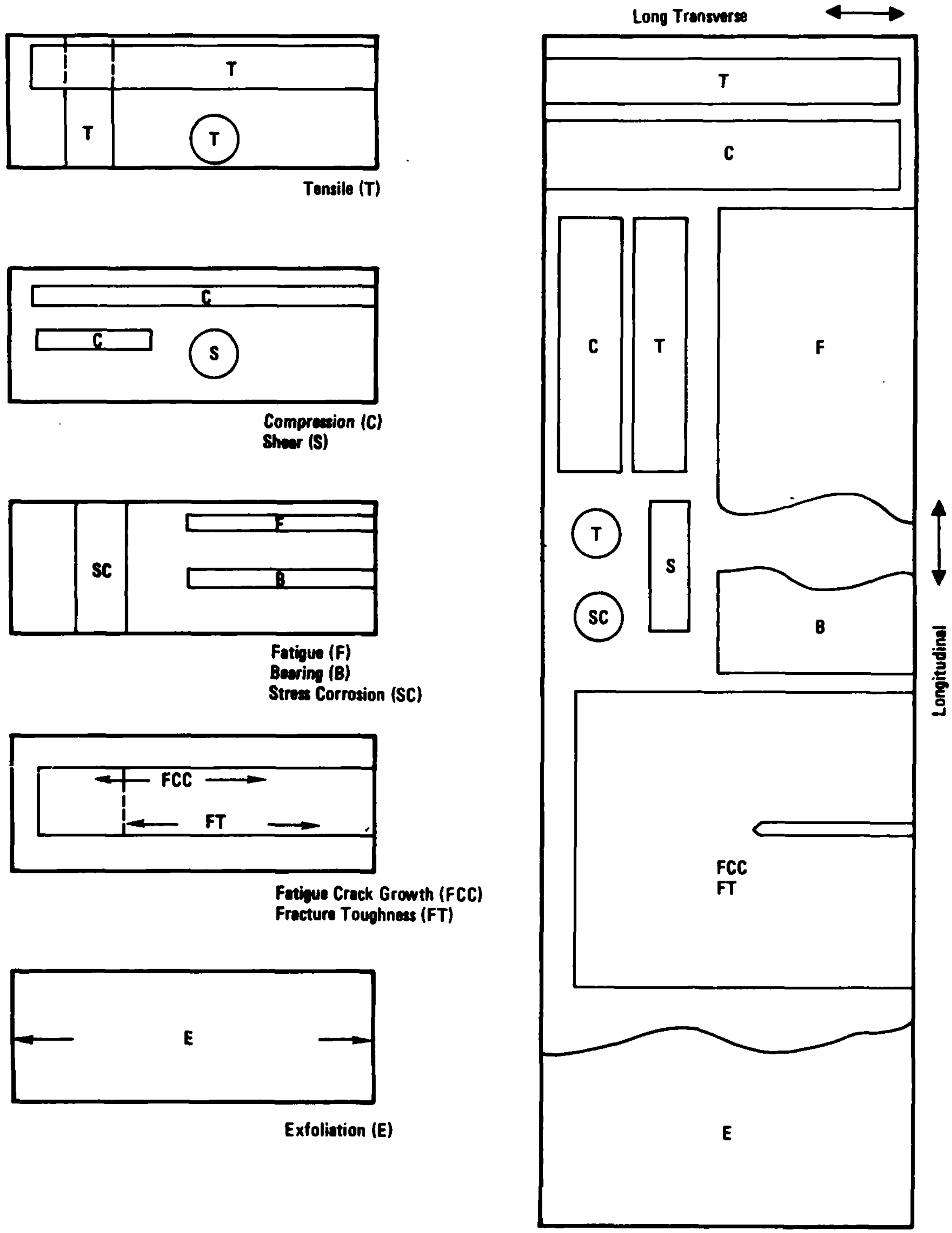


Figure 15. - Schematic of test specimen layout for flanged cap - base, LS 13116. (Not to scale)

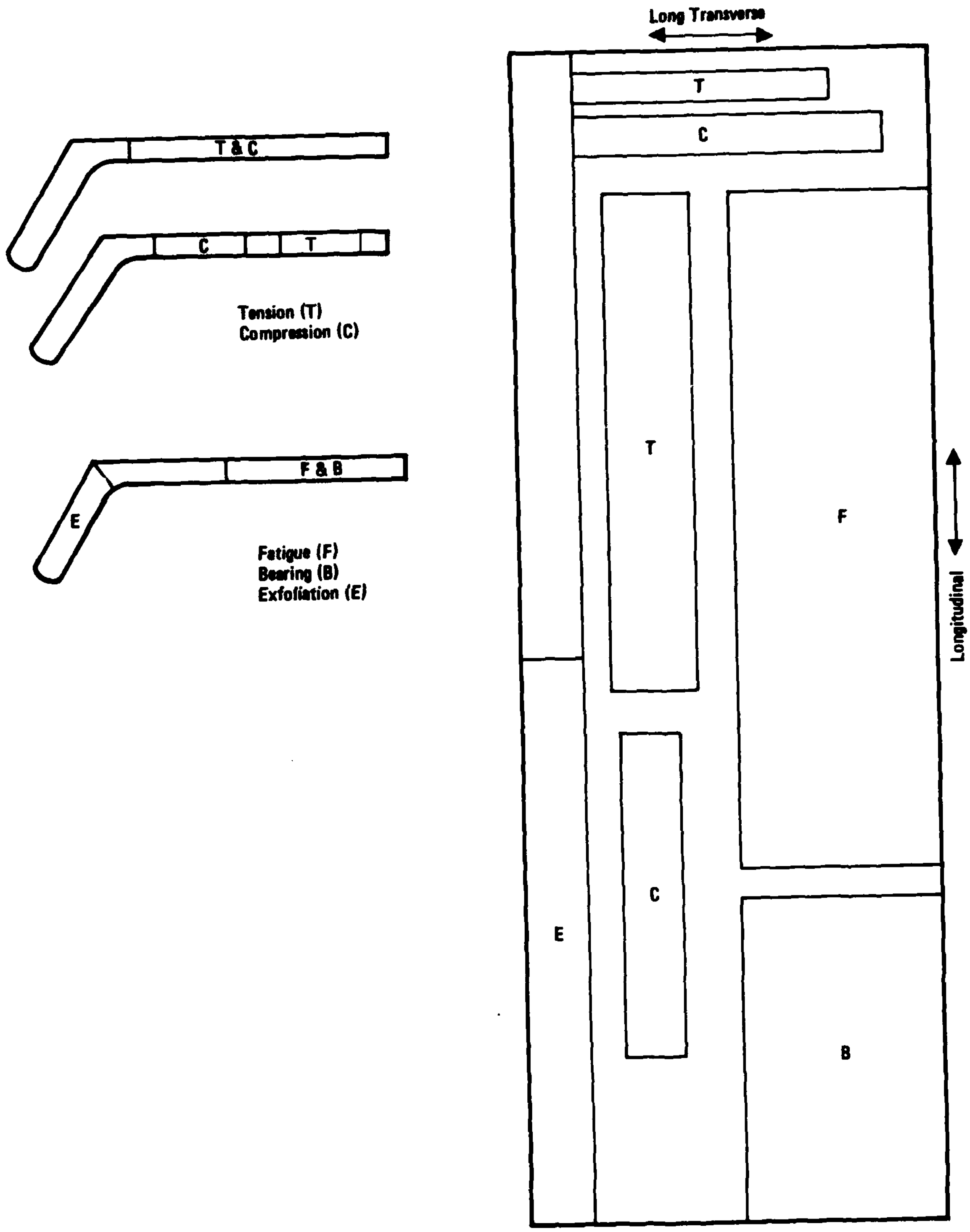


Figure 16. - Schematic of test specimen layout for flanged cap - flange, LS 13116. (Not to scale)

TEST PROCEDURES

Testing was performed in accordance with existing ASTM Standards or Recommended Practice test procedures and to established Lockheed-California Company test procedures.

Chemical Analyses

Spectrographic chemical analyses were performed in accordance with the procedures established in FED, TEST METHOD STD No. 151b, 112.1, for elements except cobalt. The cobalt was determined by the atomic absorption method using an FLL Atomic Absorption Spectro Photo Meter.

Hardness Tests

Rockwell hardness testing was conducted in accordance with procedures established in ASTM Standard E18-74. Rockwell B hardness measurements, HRB, were made on the exfoliation specimens to determine the hardness values at the surface, T/10 and T/2 planes.

Electrical Conductivity Tests

Electrical conductivity testing was conducted in accordance with procedures established in ASTM Standard B342-63. Electrical conductivity measurements were made with a Magnatest FM120 meter on the exfoliation specimens to determine the conductivity values on the surface, T/10 and T/2 planes.

Tensile Tests

Tensile tests were conducted in accordance with procedures established in ASTM Standard E8-69. Speed of testing was controlled by adjustment to a machine cross head speed to produce a strain rate of 0.005 in/in/min through the proportional limit. This same cross head was maintained after removal of the extensometer until specimen failure. Determination of the 0.2% offset yield strength and modulus were made from an autographic load versus strain curve. Elongations were computed in accordance with the ASTM procedures.

Compression Tests

Compression tests were conducted in accordance with the procedures established in ASTM Standard E9-70. Speed of testing was adjusted to a constant head travel rate which provided a strain rate of 0.005in/in/min up through the proportional limit. The specimens were strained to approximately 2.0% strain in order to provide a long enough autographic load versus strain curve for determination of 0.2% offset yield strength. The modulus was also determined from the curve.

Shear Tests

Shear tests were conducted using a rivet wire double shear fixture in a universal static test machine at a strain rate of 0.005 in/in/min.

Bearing Tests

Bearing tests were conducted in accordance with procedures established in ASTM Standard E238-68.

EXCO Exfoliation Tests

The EXCO tests were conducted in accordance with the procedures established in ASTM Standard G34-72. The total surface areas of the specimens were calculated to ensure that the amount of solution exceeded 50 milliliters per square inch.

Salt Spray Exfoliation Tests

The seven-day salt spray test was conducted in accordance with Lockheed-California Company Specification C-0521F. In this test, the specimens were exposed to a cyclic spray consisting of a solution of 5% sodium chloride adjusted with glacial acetic acid to a pH of 3.0 to 3.1 as follows:

a) 45 minute spray

b) 2 hours of dry air purge

c) 3 hours and 15 minute soak at 45-95% relative humidity

The six-hour cycle is repeated for a total period of 7 days (28 cycles). The specimens were then rinsed in water and immersed in concentrated nitric acid at room temperature followed by a water rinse and air dry.

Sea Coast Exfoliation Tests

Sea-coast exposure was conducted at the Lockheed-California Company Point Loma test site near San Diego, California. The specimens were placed on wooden racks, located approximately 100 feet from the ocean. The test surfaces were facing up and at an approximate 45-degree angle from a horizon position.

Stress Corrosion Tests

Stress corrosion tests were performed in accordance with ASTM Standard G44-75. Subsize round tensile test specimens (figures 4 and 17) were stressed in 6061-T6 aluminum alloy test fixtures by two parallel threaded fasteners, shown in figure 18. Srains for the required stresses were measured with a 0.5-inch extensometer. The test fixtures were dipped into molten Maskcoat No. 2 (oil-free cellulose acetate butyrate) before testing to prevent dissimilar metal corrosion between the test specimen and fixture during the test.

Constant Amplitude Fatigue Tests

The constant amplitude fatigue tests were conducted with Lockheed-California Company designed and built axial loading resonant-type fatigue machines, as shown in figure 19. Loadings were applied at a rate of 30 Hz. Test environment was lab air (40 ± 10% relative humidity) at room temperature.

Spectrum Fatigue Tests

The flight-by-flight spectrum fatigue tests were conducted on two 10,000-pound, closed-loop, electrohydraulic, servo-controlled, test machines, which were designed and constructed by the Lockheed-California Company.

Figure 20 shows typical test installation of two specimens. Figure 21 schematically illustrates the arrangement of a test machine and computer load programmer. In these machines, loads can be controlled within a scale accuracy of ±2% of frequencies up to 45 Hz.

As indicated in figure 21, the loading system employed the following safeguards against specimen overload.

- A load limiter was included to protect the specimens from spurious electrical signals as well as operator error by simply limiting the maximum amplitude of the signals to the preselected value.
- A high-speed dump valve, located across the hydraulic lines between the servo valve and the servo jack protected the specimens from overload in the event of internal valve leakage from the hydraulic pressure reservoir to the high-pressure side of the jack.
- A high-speed relay was located within the servo valve amplifier. In the event the rate of increase in the command signal would have exceeded that which had been programmed, this relay would have locked the servo valve and opened the high-speed dump valve.

Specimens were restrained from buckling under compression loadings by using an antibuckling bar support on the specimens. Figure 22 shows the bars installed on a specimen. Contact between the specimen and bar support assembly is through teflon and the assembly is installed by finger tightening to preclude any load being carried by the antibuckling assembly.

During testing, the specimens were examined using a 5x magnifying glass to detect incipient cracking. During the period of crack growth, a finely graduated ruler was read by a magnifying glass at intervals which were dependent upon the rate of crack growth.

The spectrum of fatigue loadings used in this testing were derived from operational service loading records for the P-3A Fleet as a part of Contract N00019-76-A-001, Order No. KZ34, "Service Life Extrusion Program (SLEP) Part I," (Reference 2), which was performed at the Lockheed-California Company. This spectrum is appropriate for use in this program, as it is basically the spectrum to which the MA87 (CT91)-T7E69 material could be subjected if used in the P-3 series aircraft. Table 3 lists the gross area stress loads of the P-3A test spectrum taken from reference 2.

To preclude the fatigue test specimens being subjected to very large numbers of flights in the testing, the test spectrum loadings were increased in magnitude by 15 to 30% to shorten the flights to crack initiation. In the table and plots of the test data, this increase is noted as stress factor (SF), by which all loadings in the spectrum have been multiplied. For example, SF = 1.30 means all loadings have been multiplied by 1.30 (increased by 30%).

All of the flight-by-flight spectrum fatigue tests were conducted in laboratory ambient conditions at room temperature (R.T.) and 40 ± 10% relative humidity (RH). The rate of load application varied from 2 to 10 Hz, with the largest load being applied at 2 Hz, and the smallest load at 10 Hz. The average rate was approximately 8-9 Hz.

Fatigue Crack Growth Tests

All fatigue crack propagation tests were conducted in closed-loop electrohydraulic fatigue machines at a frequency of either 6 or 10 Hz and a stress ratio of R=0.1. All machines were equipped with a peak and valley load monitoring system which allows the monitoring of the load signal with an accuracy of 1.0 percent of full-scale reading. Maximum peak and valley loads were monitored continuously.

The specimens were tested using standard procedures described in ASTM E 399-74. A typical test set up is shown in figure 23. During testing, the crack length was measured on both sides of a specimen to 0.001 inch using a 10x toolmaker microscope as shown in figure 24. Crack length measurements were generally taken approximately every 0.020 inch of crack growth. Specimens were tested to failure.

For the 3.5% salt solution test, the cracked region of the compact tension specimens were immersed in the solution by attaching containers to both sides of the specimens as shown in figure 25. Crack length monitoring and other test procedures for the environment tests were similar to the room environment tests.

The stress intensity factor for the compact tension specimen is:

$$K = \left[\frac{P}{t\sqrt{W}}\right]\Phi$$

where $$\Phi = \frac{3 + .8\left(\frac{a}{W}\right) - .27\ \mathrm{EXP}\left(-\frac{3a}{W}\right)\ \mathrm{SIN}\left(\frac{4\pi a}{W}\right)}{\left(1-\frac{a}{W}\right)^{3/2}}$$

and the parameters P, a, t, W are applied load, crack length, specimen thickness and specimen width, respectively. The above formula was used in this program and is considered to be valid for $0.25 \le a/w \le 0.80$.

Fracture Toughness Tests

All fracture toughness tests were conducted according to the requirements of ASTM E-399-74 using compact tension specimens.

TABLE 3. - FLIGHT-BY-FLIGHT FATIGUE TEST UPPER SURFACE STRESS SPECTRUM (P-3A OPERATIONAL MISSION MIX: SLEP, PART I) (GROSS AREA STRESS)

Mean Stress (Ksi)	± Cyclic Stress (Ksi)	Maximum Stress (Ksi)	Minimum Stress (Ksi)	Normalized Stresses: Mean / 21.2	Normalized Stresses: ± Cyclic / 21.2	Cycles (1) Applied in 4000 Flts.
Taxi and Landing						
3.8	4	7.8	−0.2	0.179	0.189	17,500
	5	8.8	−1.2		0.236	14,000
	6	9.8	−2.2		0.283	4,400
	7	10.8	−3.2		0.330	1,100
	8	11.8	−4.2		0.377	340
	9	12.8	−5.2		0.425	100
	10	13.8	−6.2		0.472	38
	11	14.8	−7.2		0.519	13
	12	15.6	−8.2		0.566	5
3.8	13	16.8	−9.2	0.179	0.613	4
Maneuvers and Gust						
−7.2	4	−3.2	−11.2	−0.340	0.189	17,500
	5	−2.2	−12.2		0.236	3,500
	6	−1.2	−13.2		0.283	930
	7	−0.2	−14.2		0.330	330
	8	+0.8	−15.2		0.377	130
	9	1.8	−16.2		0.425	65
	10	2.8	−17.2		0.472	24
	11	3.8	−18.2		0.519	10
	12	4.8	−19.2		0.566	6
	13	5.8	−20.2		0.613	4
−7.2	14	6.8	−21.2	−0.340	0.660	4

(1) 1000 flight random cycle tape made which is applied four times to get the specified number of cycles in this column in 4000 flights containing an average of about 15 cycles per flight.

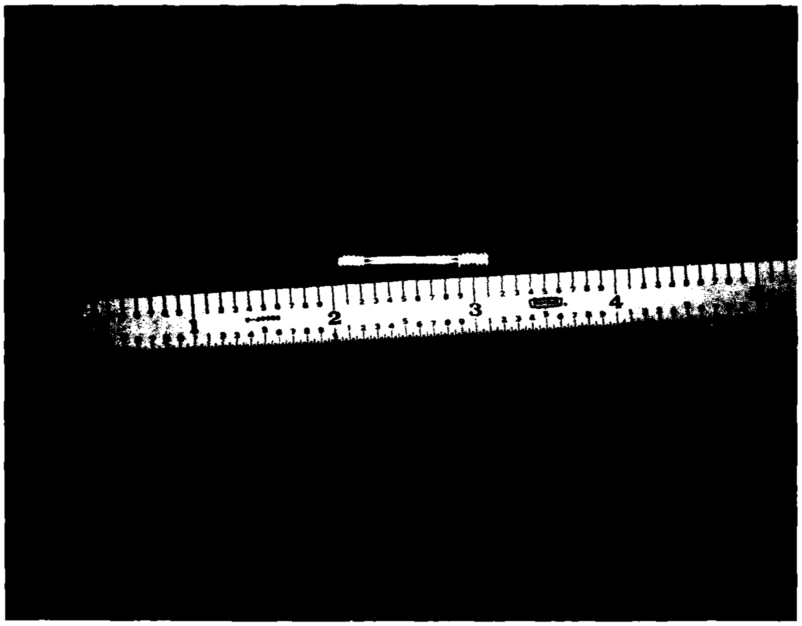


Figure 17. - Stress corrosion specimen.

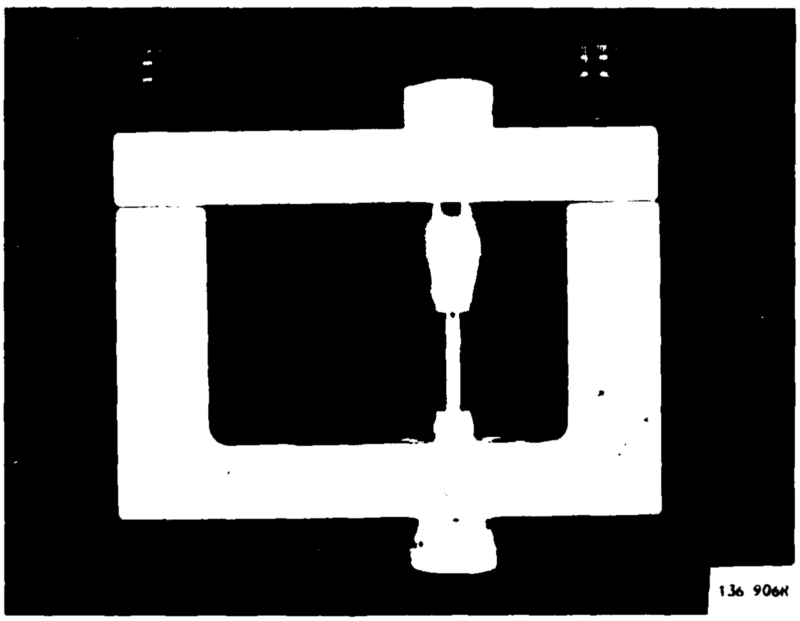


Figure 18. - Stress corrosion specimen installed in a test fixture.

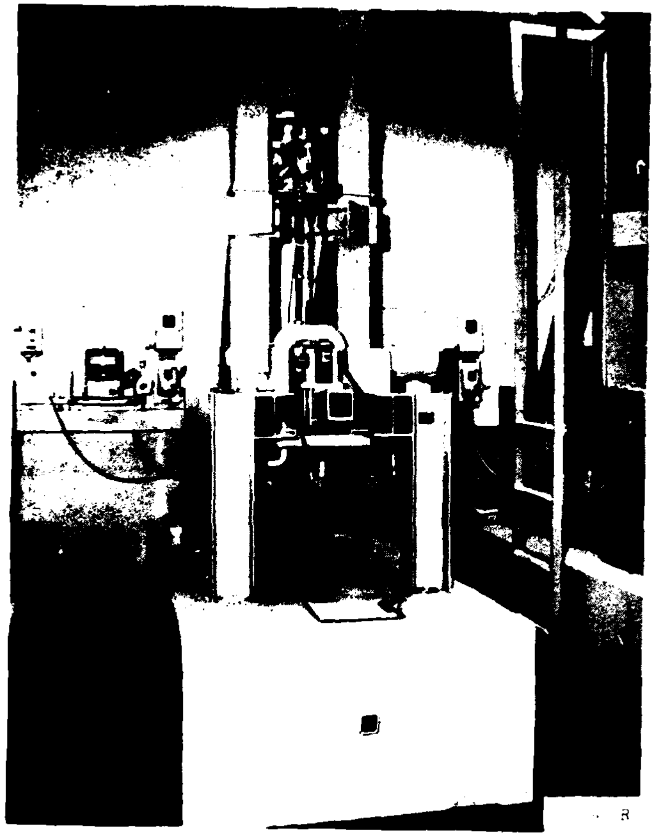


Figure 19. - Resonant fatigue machine used for constant amplitude fatigue tests.

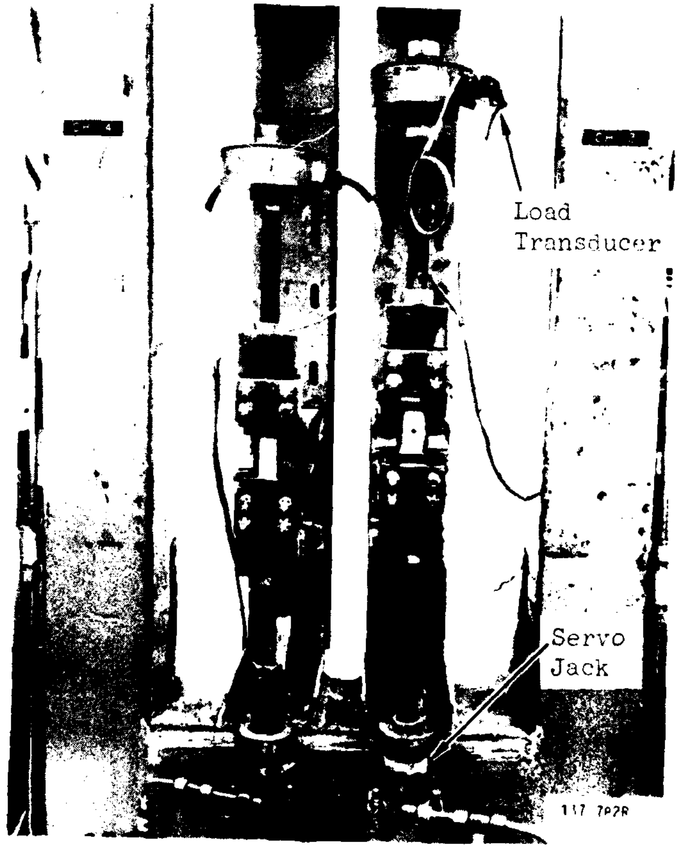


Figure 20. - Spectrum fatigue closed loop electro-hydraulic servo controlled test machines.

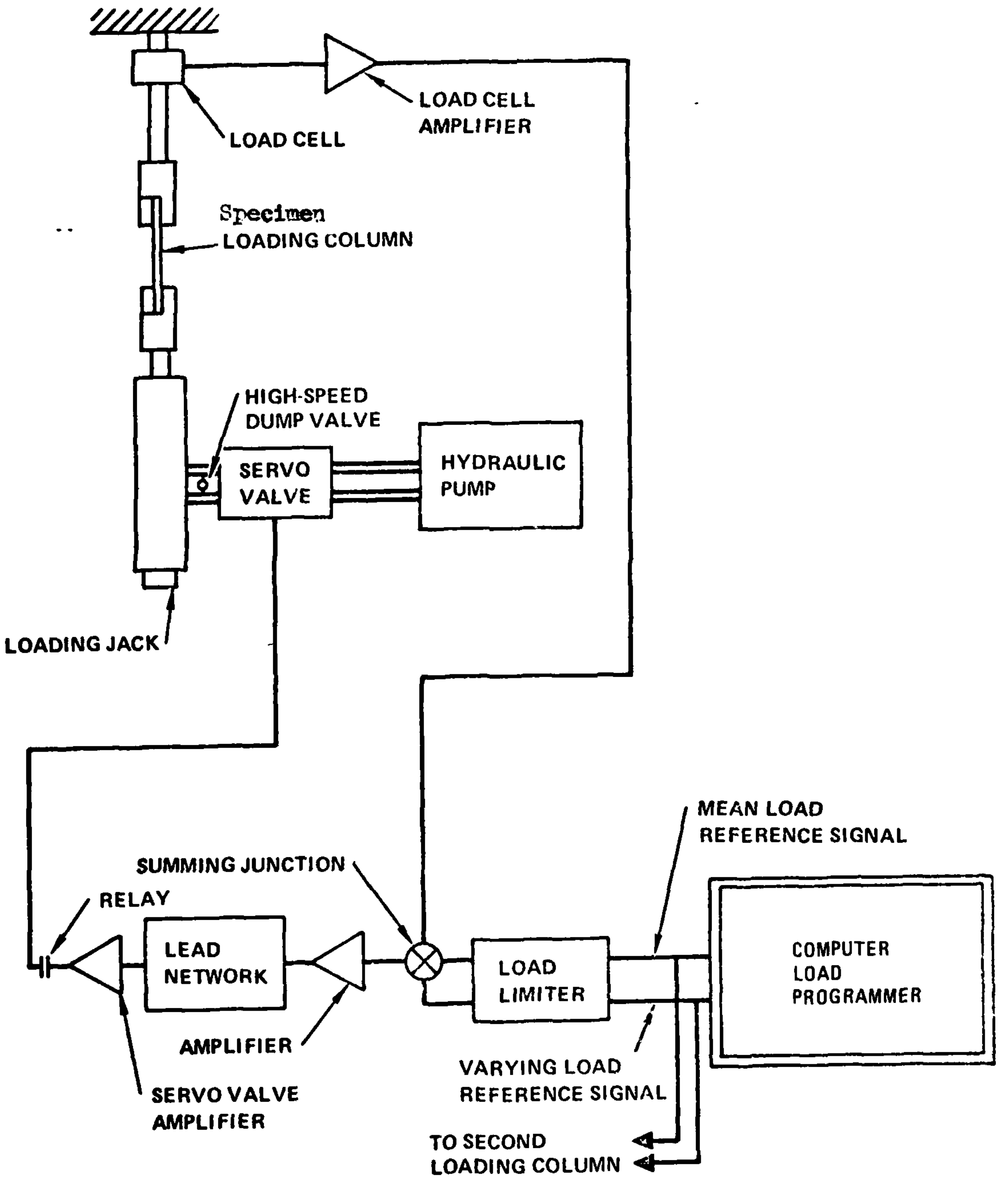


Figure 21. - Block diagram of test setup for spectrum fatigue tests.

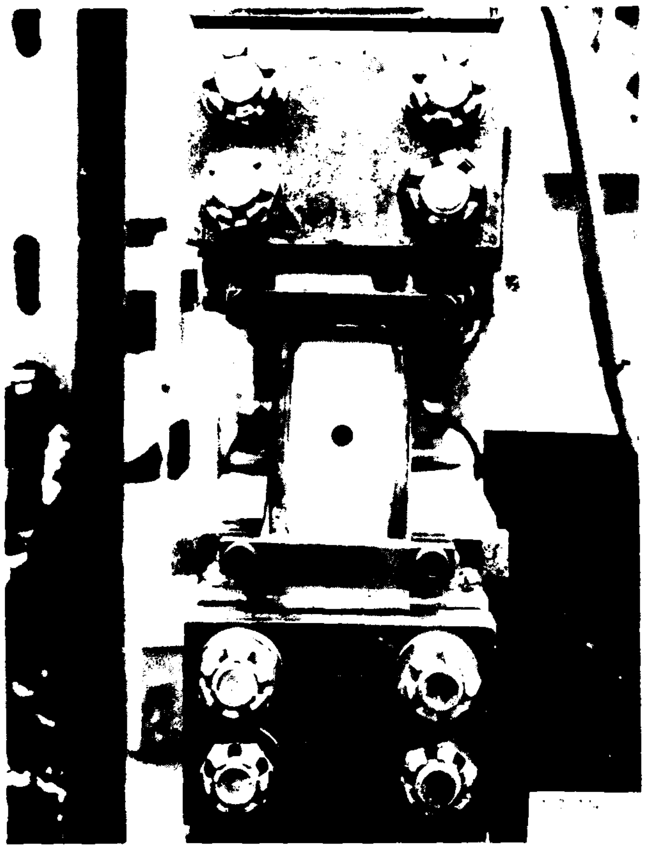


Figure 22. - Fatigue specimen installation showing anti-buckling bar support assembly.

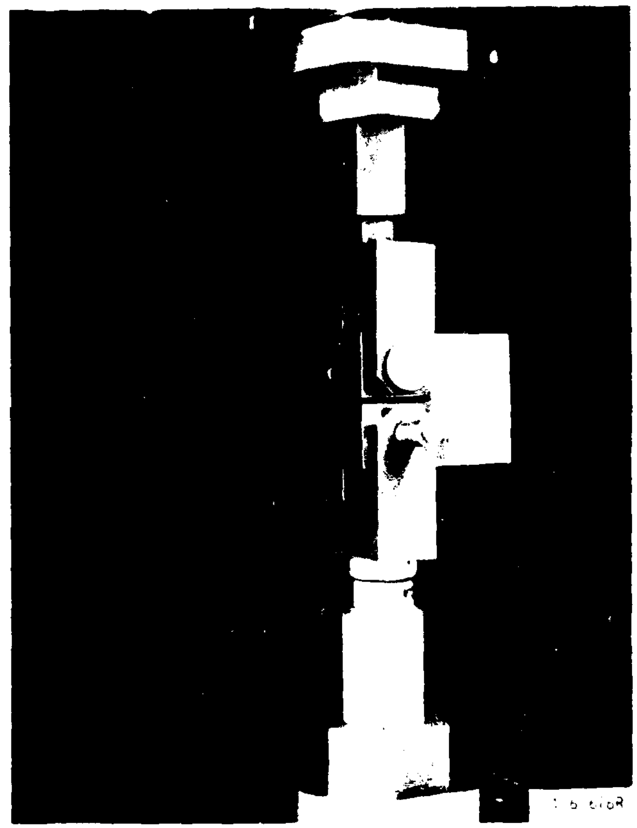


Figure 23. - Compact tension specimen under load in lab air environment.

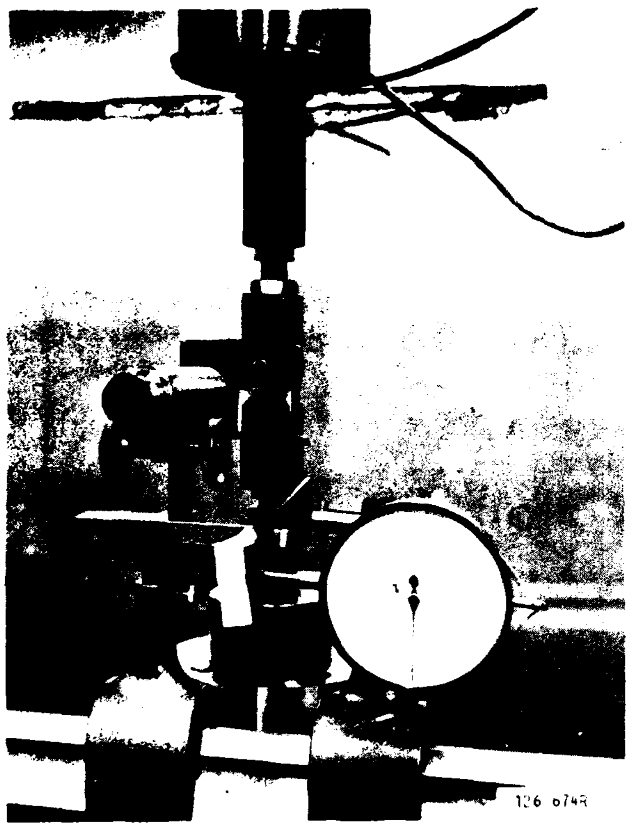


Figure 24. - Traversing stage microscope used to measure fatigue crack growth.

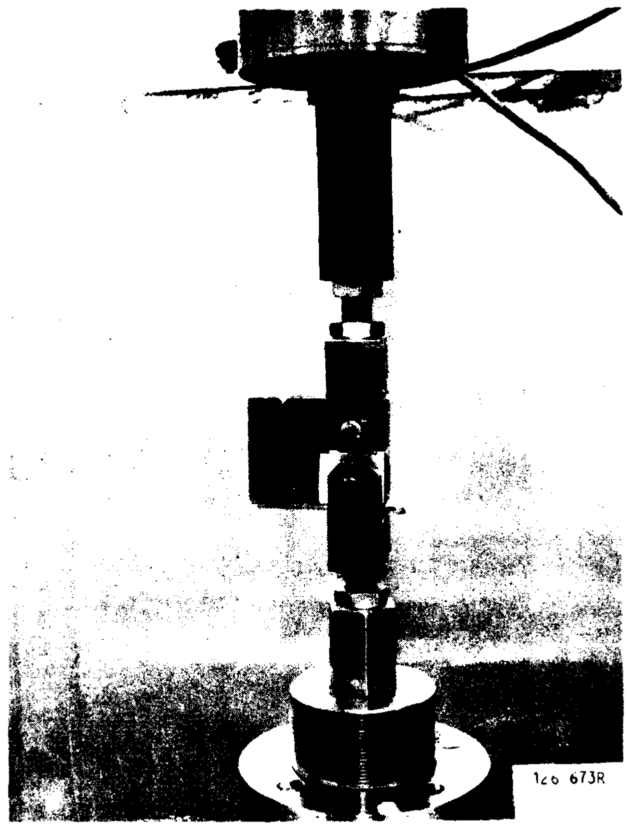


Figure 25. - Compact tension specimen under load in 3.5 percent salt solution environment.

TEST RESULTS AND DISCUSSION

Chemical Composition

The chemical compositions of the four MA87 (CT91) extrusion lots were found satisfactory when compared in table 4 with the target composition. The iron (Fe) contents were higher than the target and this agreed with Alcoa's analyses. The effect of the increased iron content was considered to have only a minor (if any) impact on material properties in this test program.

Hardness and Electrical Conductivity

Rockwell B hardness and electrical conductivity measurement at the surface, T/10 and T/2 planes shown in table 5, revealed uniform hardness and conductivity throughout the shapes, thicknesses, and lots. A reason for this behavior is the fine grain flow shown in figures 26 and 27 and fine grain microstructures shown in figures 28 through 30.

Tensile Strength and Tensile Modulus

The tensile strength and tensile modulus properties are shown in tables 6 through 8. All longitudinal tensile strengths exceeded the 82 ksi (565 MPa) target strength and only two longitudinal yield strength test values were below the 76 ksi (524 MPa) strength. A typical longitudinal stress-strain curve is shown in figure 31.

The average long traverse properties were within 6 ksi (34 MPa) of the average longitudinal strengths and the average short transverse properties were within 9 ksi of the average longitudinal strengths. In addition, the short transverse grain direction had excellent ductility.

The variation of tensile properties from lot to lot was insignificant. The thin flange had approximately 2 ksi (14 MPa) lower longitudinal tensile properties and comparable long transverse tensile properties when compared to the heavier base section of the flanged cap.

The tensile properties of MA87(CT91)-T7E69 exceed the minimum properties for 7075-T6510 extrusions. In addition, the MA87(CT91) typical tensile properties are comparable to the typical values determined for 7075-T6510 and 7050-TE73 extrusions in **reference 1.**

Compression Yield and Compression Modulus

The compression yield strength and compression modulus data are shown in tables 9 and 10. A typical compression yield stress strain curve using a 10.0 ksi (69 MPa) x 10^3 modulus is shown in figure 32.

The compression yield testing did present a problem, in that the extensometer connection was malfunctioning during the first series of tests and provided erratic modulus data for the proportional limit. The yield point data was acceptable. Therefore, additional longitudinal specimens were fabricated and tested. The modulus data for the retests were better than the first series but the scatter of 4.5 ksi (31 MPa) x 10^3 still makes the modulus data non-valid.

The compression yield data were approximately the same for both test groups and show that MA87(CT91)-T7E69 has a higher compression yield than the MIL-HDBK-5 compression yield strength "A" properties for 7075-T6 extrusions.

Shear Properties

The shear properties are shown in table 11. The properties were uniform and are higher than MIL-HDBK-5 shear properties for 7075-T6 extrusions.

Bearing Properties

The bearing ultimate and yield strengths for an e/D = 2.0 are shown in table 12. The properties for MA87(CT91)-T7E69 exceed both the bearing ultimate and bearing yield MIL-HDBK-5"A" properties for 7075-T6 extrusions.

Exfoliation Behavior

All the MA87 (CT91) specimens were resistant to exfoliation when tested in EXCO, salt spray or sea coast (8 months exposure) environments as shown in table 13. However, pitting corrosion was evident. The surface conditions of several specimens after exposure to the three environments are shown in figures 33 through 36. The pitting attacks encountered in the salt spray and EXCO tests are shown in figure 37. The resistance to exfoliation is attributed to the fine equiaxed grain structure and absence of elongated grain boundaries.

Stress Corrosion Resistance

The stress corrosion specimens failed to sustain the 45 ksi (310 MPa) target stress level in the 3.5 percent salt alternate immersion test, see table 14. Failures occurred at 35 ksi (241 MPa) within 16 days and at 25 ksi (172 MPa) within 19 days. Metallurgical examination of failed specimens showed severe pitting, but no intergranular attack, see figure 38. Therefore, MA87(CT91) must be protected from pitting corrosion to retain the load sustaining performance.

Constant Amplitude Fatigue

The constant amplitude fatigue results are shown in table 15 and figures 39 through 43. Data are presented as net stress versus cycles to failure. To obtain more test data, specimens that did not fail at approximately 10^7 cycles were rerun at higher stresses and are so noted in the data. Due to the limited number of specimens per condition and scatter, fatigue curves were not fitted to each set of data. However, standardized aluminum allowable curves (50% probability), which were derived from 7075-T6 ingot alloy data and are used for analyzing aircraft structure, have been included in the figures for comparisons. The data shows:

- The K_t = 2.7 data had more scatter than the K_t = 4.0 data.
- The fatigue strengths of the MA87(CT91)-T7E69 test data are considerably better than the standardized aluminum (7075-T6 alloy) allowable curves shown on each of the plots.

The data indicated that powder metallurgy MA87(CT91)-T7E69 extrusions could provide increased fatigue performance over ingot alloy 7075-T6 extrusions.

Spectrum Fatigue

The spectrum fatigue test crack growth data are presented in detail in table 16. These data are summarized in table 17. Comparative results for 7075-T6510 and 7050-T7E73 extrusions, previously obtained in reference 1, are also included in table 17. Crack growth curves for the MA87(CT91)-T7E69 as well as the comparative 7075-T6510 and 7050-T7E73 data are presented in figures 44 through 49.

In examining the test data, the following observations are evident:

- There is significant scatter in and between heats. For example, in Lot 1A1 of the wing spar cap, the scatter is larger than 8, i.e., 141713 divided by 16444 = 8.6, for $K_t = 2.7$ and about 7 for $K_t = 4.0$. This scatter is larger than expected for spectrum fatigue testing.

- For the flanged cap extrusions, specimens taken from the thin flange area exhibited significantly better fatigue results than specimens taken from the heavy base area, for both lots.

- The MA87(CT91)-T7E69 exhibits fatigue strengths greater than 7075-T6510 and 7050-T7E73 for $K_t = 2.7$ and considerably larger for $K_t = 4.0$. Also, slopes of the crack growth data show the crack growth rate to be slower for the MA87(CT91)-T7E69.

These spectrum fatigue tests strongly indicate that the powder metallurgy MA87(CT91)-T7E69 extrusions would provide improved fatigue performance or a potential weight savings if substituted for currently used 7075-T6510 extrusions in P-3 aircraft structure.

Fatigue Crack Growth

The fatigue crack growth data generated for L-T oriented specimens shown in table 18 are presented in figures 50 through 58. The data are shown as fatigue crack growth rate, da/dN, versus alternating stress intensity factor, ΔK. The combined data for the room temperature lab air specimens are shown in figure 59 and the combined 3.5 percent salt solution specimen data are shown in figure 60.

Photographs of the fracture surfaces included as figures 61 and 62 show the fracture surfaces were generally smooth in appearance with irregular spaced bench marks caused by changes in the load levels. Extensive tunneling, shear lip formation and curving of the crack path occurred in the later stage of testing. The stain on the fracture surfaces of the 3.5 percent salt solution are due to oxidation. The observed fracture behavior is similar to that of L-T oriented compact 7075-T76511 extrusions evaluated by Lockheed-California Company in reference 3.

Comparison of this MA87(CT91)-T7E69 data with previous Lockheed-California Company data generated for 7075-T76511 extrusions in reference 3, showed comparable crack growth behavior for both materials in the L-T specimen orientation. The crack growth data generated in this program were not compared to 7075-T6510 and 7050-T7E73 crack growth data of reference 1 since the data in the reference were generated for 0.090 inch thick center crack panels taken from wing plank extrusions.

Fracture Toughness

A summary of the fracture toughness test data for L-T oriented specimens is shown in table 19. Locations for the various crack length measurements are shown in figure 63. Photographs of the fracture surfaces are shown in figure 64.

Review of the data in table 19 shows the specimens from lot 2A1 have a higher average K_{IC} value and less scatter of individual values than the specimens from lot 2A2. Results from specimens Y4 and Y5 from lot 2A2 were judged to be invalid due to substantial crack front variation in the-thru-thickness direction. In addition, specimens Y2 and Y6 which yield lower K_{IC} values are also observed to have shear lip formation during the pre-cracking phase. This is evident in the comparison of the fracture surfaces in figure 64. The figure shows specimens from lot 2A1 have uniform fatigue pre-cracking regions with minimal shear lip formation and tunneling; whereas, specimens from lot 2A2 show substantially more fracture surface irregularities.

The L-T fracture toughness behavior of the MA87(CT91)-T7E69 specimens showed no significant improvement when compared with similar published data for 7075-T6 extrusions.

TABLE 4. - CHEMICAL COMPOSITION

Shape	Lot	Location	Composition, Percent					
			Zn	Mg	Cu	Co	Fe	Si
Wing Spar Cap LS 9788	1A1	Cap	6.35	2.17	1.38	.428	.125	.071
	1A2	Cap	6.70	2.14	1.52	.431	.133	.074
Flanged Cap LS 13116	2A1	Base	6.54	2.28	1.46	.448	.127	.075
		Flange	6.40	2.53	1.30	.435	.110	.062
	2A2	Base	6.57	2.54	1.58	.438	.120	.064
		Flange	6.40	2.36	1.40	.442	.100	.060
Target			6.5	2.5	1.5	.4	.10 max	.10 max

TABLE 5. - HARDNESS AND ELECTRICAL CONDUCTIVITY VALUES

Shape	Lot	Area	Rockwell B Hardness			Electrical Conductivity, % IACS		
			Surface	T/10 Plane	T/2 Plane	Surface	T/10 Plane	T/2 Plane
Wing Spar Cap LS9788	1A1	Cap	90.5	90	89.5	39.0	39.0	39.0
		Web	–	90	90	38.5	38.5	38.5
	1A2	Cap	90	90	90	39.0	39.0	39.0
		Web	–	90	90	39.0	39.0	39.0
Flanged Cap LS13116	2A1	Base	89.5	90	90	39.5	39.0	39.0
		Flange	90	90	88.5	39.0	39.0	39.0
	2A2	Base	90	90	90	39.25	39.0	39.0
		Flange	90	90	88.5	39.0	38.75	38.5

TABLE 6. - TENSILE AND MODULUS PROPERTIES OF WING SPAR CAP LS9788

Lot	Grain Direct	Ultimate		Yield		Elong	Modulus x 10^3	
		ksi	MPa	ksi	MPa	%(1)	ksi	MPa
1A1	Long	87.9	606	81.6	563	11	11.2	77
		86.7	597	79.9	551	10	11.2	77
		87.2	601	79.2	546	11	11.0	76
		87.8	605	80.1	552	10	11.3	78
		88.3	609	81.1	559	10	11.1	76
	Avg.	87.6	604	80.4	554	10	11.2	77
	Long	82.3	567	74.6	514	11	10.4	72
		82.5	569	75.0	517	10	10.7	74
	Trans	82.5	569	75.2	518	10	10.6	73
		83.3	574	75.2	518	14	10.0	69
		81.8	564	74.3	505	12	10.4	72
	Avg.	82.5	569	74.9	516	11	10.4	72
	Short	82.3	567	74.8	516	10	11.6	80
		82.2	567	74.2	512	10	11.7	81
	Trans	82.5	569	74.1	511	12	11.5	79
	Avg.	82.3	567	74.4	513	11	11.6	80
1A2	Long	87.8	606	81.4	561	14	11.8	82
		86.2	594	79.6	549	14	10.8	75
		86.4	596	78.9	544	10.	10.7	74
		87.5	604	75.8	523	10	10.4	72
		86.9	599	79.5	548	13	10.1	70
	Avg.	87.0	600	79.0	545	12	10.8	75
	Long	82.9	572	75.3	519	10	11.0	76
		82.3	567	74.8	516	10	11.0	76
	Trans	83.2	574	76.1	525	15	10.9	75
		82.6	570	73.8	509	15	10.4	72
		83.5	576	76.0	524	15	11.6	80
	Avg.	82.9	572	75.2	519	13	11.0	76
	Short	82.3	567	74.3	512	12	11.1	77
		83.2	574	76.1	525	11	11.1	77
	Trans	84.2	581	76.8	530	14	11.5	79
	Avg.	83.2	574	75.3	519	12	11.2	77

(1) Elong in 1.0 in (25.4 mm) for Long and Long Trans and in 0.5 in (12.7 mm) for Short Trans.

TABLE 7. - TENSILE AND MODULUS PROPERTIES OF FLANGED CAP LS13116, LOT 2A1

Grain Direct	Base Section							Flange Section						
	Ultimate		Yield		Elong	Modulus x 10^3		Ultimate		Yield		Elong	Modulus x 10^3	
	Ksi	MPa	Ksi	MPa	%(1)	Ksi	MPa	Ksi	MPa	Ksi	MPa	%(1)	Ksi	MPa
Long	88.5	610	82.3	567	11	10.4	72	86.2	594	80.0	552	10	10.3	71
	88.0	607	81.2	560	12	10.4	72	87.1	601	74.1	511	10	8.7	60
	88.0	607	82.3	567	12	10.4	72	86.8	598	78.1	538	11	9.1	63
	87.6	604	81.0	558	12	10.6	74	86.6	597	80.4	554	11	10.2	70
	88.2	608	82.1	573	12	10.4	72	85.8	592	79.6	547	10	10.4	72
Avg.	88.1	607	81.8	564	12	10.4	72	86.5	596	79.4	547	10	9.7	67
Long	84.2	580	78.3	540	13	10.5	73	83.6	576	76.2	525	12	12.3	85
	83.4	575	76.7	529	11	10.4	72	84.7	584	76.2	525	14	11.2	77
Trans	83.3	574	76.2	525	13	10.5	73	85.4	589	77.7	536	14	10.6	73
	83.5	576	76.6	528	12	10.4	72	84.6	583	77.2	532	10	11.1	77
	83.9	578	77.2	532	10	10.5	73	83.7	577	77.0	531	14	11.8	82
Avg.	83.7	577	77.0	531	12	10.5	73	84.4	581	76.7	529	13	11.4	79
Short	83.7	577	75.6	522	16	10.9	78	No Data						
	83.5	576	75.2	519	14	10.1	69							
Trans	79.9	551	72.4	499	12	10.1	69							
Avg.	82.4	568	74.4	513	14	10.4	72							

(1) Elong in 1.0 in (25.4 mm) for Long and Long Trans and in 0.5 in (12.7 mm) for Short Trans

TABLE 8. - TENSILE AND MODULUS PROPERTIES OF FLANGED CAP LS13116. LOT 2A2

Grain Direct	Base Section							Flange Section						
	Ultimate		Yield		Elong	Modulus x 10^3		Ultimate		Yield		Elong	Modulus x 10^3	
	Ksi	MPa	Ksi	Mpa	%(1)	Ksi	MPa	Msi	MPa	Ksi	MPa	%(1)	Ksi	MPa
Long	88.1	607	81.4	561	13	10.2	70	86.1	594	79.3	547	13	10.5	73
	89.0	614	83.0	572	11	10.4	72	86.6	597	79.1	546	9	10.4	72
	88.2	608	81.7	563	12	10.4	72	87.7	605	80.9	558	12	10.8	75
	88.0	607	82.2	567	13	10.4	72	85.8	592	78.7	543	12	11.9	82
	87.0	606	80.9	558	13	10.1	69	85.9	592	78.7	543	12	11.0	76
Avg.	88.2	608	81.8	564	12	10.3	71	86.4	596	79.3	547	12	10.9	75
Long	83.6	576	76.8	529	13	10.3	71	83.5	591	76.4	527	14	10.8	75
	83.3	574	76.5	527	10	10.3	71	83.8	578	76.2	525	10	12.5	86
Trans	83.6	576	76.6	528	11	10.5	73	84.6	583	76.9	530	12	10.6	74
	83.8	578	76.5	527	12	10.0	69	85.1	587	76.2	525	14	10.0	69
	82.4	568	75.7	522	8	10.2	70	85.0	586	76.9	530	10	11.0	76
Avg.	83.5	576	76.4	527	11	10.3	71	84.4	581	76.5	527	12	11.0	76
Short	81.0	558	71.1	490	16	10.5	73	No Data						
	82.5	569	74.8	516	14	10.3	71							
Trans	83.3	574	72.4	499	14	9.8	67							
Avg.	82.3	567	72.8	502	15	10.2	70							

(1) See Table 7

TABLE 9. - COMPRESSION YIELD STRENGTH AND MODULUS PROPERTIES

Shape	Lot	Location	Grain Direct	Compression Yield Ksi	Compression Yield MPa	Modulus x $10^{3(1)}$ Ksi	Modulus x $10^{3(1)}$ MPa
Wing Spar Cap LS9788	1A1	Cap	L	82.0	565	9.0	62
			L	79.4	547	9.8	68
			L	79.1	546	9.0	62
			Ave	80.1	552		
			LT	79.3	547	11.5	79
			LT	79.1	546	9.8	68
			LT	80.5	555	11.1	77
			Ave	79.6	549		
	1A2	Cap	L	81.0	558	9.3	64
			L	79.9	550	9.5	66
			L	82.2	567	9.2	63
			Ave	81.0	558		
			LT	81.3	560	9.9	68
			LT	81.1	559	9.7	67
			LT	79.7	549	9.8	62
			Ave	80.7	556		
Flanged Cap LS13116	2A1	Base	L	80.6	556	9.6	66
			L	85.4	589	19.4	134
			L	85.5	589	10.5	72
			Ave	83.8	578		
			LT	85.3	588	21.9	151
			LT	86.0	593	22.5	155
			LT	85.6	590	22.3	154
			Ave	85.6	590		
		Flange	L	86.2	594	9.9	68
			L	84.4	581	9.9	68
			L	86.3	594	10.5	72
			Ave	85.6	590		
	2A2	Base	L	82.1	566	20.1	138
			L	81.7	563	18.8	130
			L	82.4	568	10.0	69
			Ave	82.1	566		
			LT	77.5	533	8.4	58
			LT	81.7	563	9.9	68
			LT	82.5	569	21.6	149
			Ave	80.6	556		
		Flange	L	85.4	589	10.7	74
			L	85.3	588	20.7	143
			L	83.6	576	20.3	140
			Ave	84.8	585		

(1) Modulus data is non-valid due to excessive scatter and is reported for information only.

TABLE 10. - RETEST OF COMPRESSION YIELD STRENGTH AND MODULUS PROPERTIES

Shape	Lot	Location	Grain Direct	Compression Yield		Modulus x 10[3(1)]	
				Ksi	MPa	Ksi	MPa
Wing Spar Cap LS9788	1A1	Cap	L	79.1	546	11.5	79
			L	80.8	557	9.2	63
			L	80.7	556	–	–
			L	81.1	559	9.4	65
			Ave	80.2	553	10.0	69
	1A2	Cap	L	81.0	558	9.0	62
			L	81.2	560	8.6	59
			L	79.5	548	10.1	70
			L	80.8	557	10.1	79
			Ave	80.6	556	9.7	67
Flanged Cap LS13116	2A1	Base	L	81.6	563	9.2	63
			L	78.7	543	8.5	59
			L	79.7	550	10.4	71
			L	81.1	559	9.9	68
			Ave	80.2	553	9.5	66
		Flange	L	81.5	562	8.0	55
			L	84.7	584	9.0	62
			L	83.0	572	8.0	55
			L	82.8	571	9.2	63
			Ave	83.0	572	8.5	59
	2A2	Base	L	82.7	570	11.3	78
			L	81.2	560	–	–
			L	81.5	562	8.5	59
			L	82.6	569	–	–
			Ave	82.0	565	9.9	68
		Flange	L	80.5	555	8.1	56
			L	80.6	556	10.0	69
			L	79.5	548	10.0	69
			L	81.0	558	8.0	55
			Ave	80.4	554	9.0	62

(1) Modulus data is non-valid due to scatter and is reported for information only.

TABLE 11. - SHEAR PROPERTIES

Shape	Lot	Location (1)	Shear Ksi	Shear MPa
Wing Spar Cap LS9788	1A1	Cap	48.9	337
			49.4	340
			48.7	336
		Ave	49.0	338
	1A2	Cap	49.2	339
			49.1	338
			48.3	333
		Ave	48.9	337
Flanged Cap LS13116	2A1	Base	49.7	342
			49.6	342
			49.5	341
			50.1	345
		Ave	49.7	346
	2A2	Base	49.3	340
			49.1	338
			49.4	340
			48.4	340
		Ave	49.1	338

(1) Specimen length was parallel to longitudinal grain direction. Shear plane was perpendicular to the longitudinal grain direction.

TABLE 12. - BEARING AND BEARING YIELD STRENGTH, e/D=2.0

Shape	Lot	Location	Grain Direct	Ultimate Ksi	Ultimate MPa	Yield Ksi	Yield MPa
	1A1	Cap	L	164.0	1131	145.0	1000
Wing			L	161.6	1114	122.7	856
			L	166.8	1150	126.6	873
Spar			Ave	164.1	1131	133.4	919
	1A2	Cap	L	170.6	1176	133.1	918
Cap			L	163.5	1127	133.1	918
			L	162.3	1119	127.3	878
LS9788			Ave	165.5	1141	131.2	905
	2A1	Base	L	161.0	1110	126.0	869
			L	169.4	1168	138.8	957
			L	162.3	1119	125.0	862
			Ave	164.2	1132	128.9	889
Flanged		Flange	L	169.4	1168	134.5	927
			L	172.7	1190	130.3	898
			L	165.8	1143	126.6	873
Cap			Ave	169.3	1167	130.5	900
	2A2	Base	L	166.9	1151	135.3	933
			L	165.2	1139	134.8	929
LS13116			L	169.7	1170	120.0	827
			Ave	167.2	1160	130.0	896
		Flange	L	173.7	1198	137.5	948
			L	175.8	1213	140.0	965
			L	171.3	1181	138.1	952
			Ave	173.6	1197	138.5	955

TABLE 13. - EXFOLIATION TEST RESULTS

Shape	Lot	Location	Surface	Exfoliation Rating(1)		
				EXCO(2)	Salt(3) Spray	Sea(4) Coast
Wing	1A1	Cap	T	P	SP	P
			T/10	P	SP	P
Spar			T/2	P	SP	P
Cap		Web(5)	T-T/10	P	SP	P
LS9788			T/2	P	SP	P
	1A2	Cap	T	P	SP	P
			T/10	P	SP	P
			T/2	P	SP	P
		Web(5)	T-T/10	P	SP	P
			T/2	P	SP	P
Flanged	2A1	Base	T	P	SP	P
			T/10	P	SP	P
			T/2	P	SP	P
Cap		Flange	T	P	SP	P
			T/10	P	SP	P
LS13116			T/2	P	SP	P
	2A2	Base	T	P	SP	P
			T/10	P	SP	P
			T/2	P	SP	P
		Flange	T	P	SP	P
			T/10	P	SP	P
			T/2	P	SP	P

(1) Rated per ASTM-G34, P = Pitting, SP = Slight Pitting
(2) Tested per ASTM-G34
(3) 7 Day Modified ASTM Acetic Acid Salt Intermittent Spray (MASTMAAIS)
(4) Seacoast exposure at Point Loma, San Diego, CA. for 8 months.
(5) Machine cut through taper section exposed T through T/10 planes.

TABLE 14. - STRESS CORROSION RESULTS OF FLANGED CAP-BASE, LS13116 .

Lot	Stress Ksi	Stress MPa	Number of Specimens	Exposure Time, Days
2A1	45	310	3	4, 5, 11
2A2	45	310	3	12, 12, 12
2A1	35	241	3	16, <30(1), <30(1)
2A2	35	241	3	<30(1), <30(1), 30NF(2)
2A1	25	172	3	19 28 28
2A2	25	172	3	19 28 30NF(2)

(1) Failed under maskant. Failure not detected until removal from fixture.

(2) No failure.

TABLE 15. - CONSTANT AMPLITUDE FATIGUE TEST DATA

Shape	K_t	R	Net Stress Ksi	Net Stress MPa	Cycles to Failure	Remarks
Wing Spar Cap, LS9788, Lot 1A1	2.7	+0.1	25.0	172	166,388	
			20.0	138	13,536,150	No Failure
			27.5	190	15,320,700	Rerun of Runout
			30.0	207	39,600	No Failure
			25.0	172	62,858	
			29.9	206	29,520	
Wing Spar Cap, LS9788, Lot 1A2	2.7	+0.1	27.5	190	102,770	
			25.0	172	998,498	
			25.0	172	693,805	
			30.0	207	86,215	
			23.9	165	8,599110	Failure in Grip
Flanged Cap, Base, LS13116, Lot 2A1	2.7	+0.1	30.0	207	2,261,045	
			27.5	190	85,800	
			35.0	241	29,802	
			25.0	172	825,475	
			20.0	138	10,000,000	No Failure
			32.5	224	29,700	Rerun of Runout
			30.0	207	48,400	
Flanged Cap, Flange, LS13116, Lot 2A1	2.7	+0.1	25.0	172	147,245	
			35.9	248	91,132	
			20.0	138	11,791,650	No Failure
			27.5	190	16,743,125	Rerun of Runout
			30.0	207	38,047	No Failure
			25.0	172	51,982	
FLanged Cap, Base, LS13116, Lot 2A2	2.7	+0.1	26.5	183	135,225	
			29.9	206	35,690	
			20.0	138	16,601,775	No Failure
			27.5	190	53,965	Rerun of Runout
			30.0	207	48,282	
			25.0	172	10,980,000	No Failure
			32.5	224	29,475	Rerun of Runout
Flanged Cap, Flange, LS13116, Lot 2A2	2.7	+0.1	29.0	200	325,295	
			30.0	207	10,016,825	No Failure
			25.0	172	10,000,000	No Failure
			32.5	224	29,348	Rerun of Runout
			30.0	207	35,775	
			20.0	138	10,000,000	No Failure
			27.5	190	16,772,800	Rerun of Runout
						No Failure

TABLE 15. - CONSTANT AMPLITUDE FATIGUE TEST DATA (Continued)

Shape	K_t	R	Net Stress Ksi	Net Stress MPa	Cycles to Failure	Remarks
Wing Spar Cap, LS9788, Lot 1A1	4.0	+0.1	15.0	103	17,468,390	No Failure
			30.0	207	10,575	Rerun of Runout
			19.2	132	10,124,000	No Failure
			20.0	138	178,760	
			20.0	138	78,540	
			25.0	172	38,700	
Wing Spar Cap, LS9788, Lot 1A2	4.0	+0.1	15.0	103	10,260,000	No Failure
			27.5	190	15,180	Rerun of Runout
			25.0	172	30,870	
			20.0	138	208,845	
			31.3	216	10,989	
			20.0	138	500,378	
Flanged Cap, Base, LS13116, Lot 2A1	4.0	+0.1	20.0	138	78,400	
			31.2	215	12,915	
			20.0	138	60,775	
			18.0	124	186,638	
			15.0	103	10,000,000	No Failure
			27.5	190	18,400	Rerun of Runout
Flanged Cap, Flange, LS13116 Lot 2A1	4.0	+0.1	20.0	138	10,000,000	No Failure
			25.0	172	26,875	
			19.0	131	10,000,000	No Failure
			15.0	103	10,966,800	No Failure
			27.5	190	13,860	Rerun of Runout
			20.0	138	142,120	
Flanged Cap, Base, LS13116 Lot 2A2	4.0	+0.1	31.3	216	13,120	
			20.0	138	104,490	
			15.0	103	12,642,075	No Failure
			25.0	172	21,390	Rerun of Runout
			19.0	131	71,600	
			20.0	138	116,400	
Flanged Cap, Flange, LS13116, Lot 2A2	4.0	+0.1	20.0	138	10,475,500	No Failure
			25.0	172	21,070	
			15.0	103	10,000,000	No Failure
			30.0	207	16,920	Rerun of Runout
			25.0	172	32,982	
			20.0	138	134,055	

TABLE 15. - CONSTANT AMPLITUDE FATIGUE TEST DATA (Continued)

Shape	K_t	R	Net Stress Ksi	Net Stress MPa	Cycles to Failure	Remarks
Wing Spar Cap, LS9788, Lot 1A1	2.7	+0.5	32.5	224	192,375	
			25.0	172	10,596,000	No Failure
			37.5	259	12,159,400	Rerun of Runout No Failure
			30.0	207	10,004,000	No Failure
			40.0	276	42,130	Rerun of Runout
			31.5	217	3,652,690	
			35.0	241	118,320	
Flanged Cap, Base, LS13116, Lot 2A1	2.7	+0.5	27.5	190	10,016,800	No Failure
			30.0	207	134,610	
			25.0	172	10,287,500	No Failure
			37.5	259	72,455	Rerun of Runout
			29.0	200	14,151,150	

TABLE 16. - SPECTRUM FATIGUE TEST DATA

Shape	K_t	Stress Factor	Specimen	Flights	Crack Length, in(1) L	R
Wing Spar, Cap, LS9788 Lot 1A1	2.7	1.30	A6	16,444	Failed	
			A7	38,047	Failed	
			A81	141,713	Failed	
			A91	72,000	–	0.21
				73,000	–	0.24
				75,000	–	0.33
				76,000	–	0.36
				77,000	–	0.36
				78,000	0.10	Edge
				78,360	Failed	
Wing Spar Cap, LS9788 Lot 1A2	2.7	1.30	B6	21,000	0.09	–
				23,000	0.11	–
				26,000	0.12	–
				30,000	0.16	–
				35,000	0.165	0.10
				37,000	0.175	0.125
				39,000	0.22	0.16
				40,000	0.24	0.16
				42,000	0.24	0.21
				44,000	0.27	0.24
				46,800	0.30	0.28
				48,000	0.32	0.30
				50,000	0.34	0.34
				51,721	Failure	
			B7	18,650	Failure	
Flanged Cap Base, LS13116 Lot 2A1	2.7	1.30	X23	23,000	0.20	0.18
				24,000	0.24	0.23
				26,000	0.32	0.30
				27,000	0.36	0.40
				28,000	0.42	0.50
				28,360	Failure	
			X33	31,000	–	0.08
				33,000	–	0.12
				34,000	–	0.16
				35,000	–	0.19
				36,000	–	0.22
				37,000	–	0.26
				38,000	–	0.37
				39,000	–	0.44
				39,800	0.06	0.48
				40,000	0.07	0.48
				40,500	Failure	

(1) L & R refer to cracking on left (L) or right (R) side of hole.

TABLE 16. - SPECTRUM FATIGUE TEST DATA (Continued)

Shape	K_t	Stress Factor	Specimen	Flights	Crack Length, in(1) L	R
Flanged Cap Base LS13116 Lot 2A2	2.7	1.30	Y23	14,480	–	0.12
				15,300	–	0.16
				16,000	–	0.18
				18,000	0.05	0.29
				19,000	0.12	0.32
				20,000	0.17	0.38
				21,000	0.39	0.44
				22,000	0.41	0.50
				22,480	Failure	
			Y33	27,000	0.11	–
				36,360	Failure	
Flanged Cap, Flange, LS13116 Lot 2A1	2.7	1.30	X211	124,000	0.11	–
				127,000	0.18	–
				128,000	0.18	–
				131,000	0.28	–
				132,000	0.30	–
				134,000	Edge	0.01
				134,330	Failure	
			X231	69,000	–	0.10
				71,000	–	0.16
				72,000	–	0.21
				73,000	–	0.28
				74,000	–	0.34
				76,000	–	0.36
				77,000	–	0.41
				78,000	–	0.44
				79,000	–	0.46
				80,000	–	0.48
				81,000	–	0.51
				81,930	Failure	
Flanged Cap Flange, LS13116 Lot 2A2	2.7	1.30	Y211	47,800	Failure	
			Y231	160,000	No Failure	
Wing Spar Cap, LS9788 Lot 1A1	4.0	1.15	A60	151,000	No Failure	
			A70	23,000	0.05	0.02
				25,110	0.07	0.06
				28,000	0.10	0.10
				31,000	0.13	0.16
				36,000	0.13	0.17
				38,000	0.14	0.17
				39,000	0.14	0.18
				40,000	0.14	0.18
				43,000	0.24	0.28
				44,000	0.28	0.30
				47,000	0.30	0.30
				51,270	Failure	

TABLE 16. - SPECTRUM FATIGUE TEST DATA (Continued)

Shape	K_t	Stress Factor	Specimen	Flights	Crack Length, in[(1)] L	R
Wing Spar Cap LS9788 Lot 1A1	4.0	1.15	A82	19,710	0.14	0.28
				20,000	0.16	0.30
				21,000	0.18	0.33
				22,480	Failure	
			A92	29,290	Grip Failure	
Wing Spar Cap, LS9788 Lot 1A2	4.0	1.15	B60	100,000	No Failure	
			B70	20,000	0.06	0.05
				28,000	0.24	0.26
				30,800	0.32	0.36
				31,600	Failure	
Flange Cap Base, LS13116 Lot 2A1	4.0	1.15	X43	15,000	0.05	0.10
				19,000	0.10	0.175
				20,000	0.11	0.185
				24,500	0.17	0.28
				26,000	0.22	0.35
				27,000	0.26	0.42
				27,750	Failure	
			X53	100,000	No Failure	
Flanged Cap Base, LS13116 Lot 2A2	4.0	1.15	Y43	7,000	0.04	0.05
				8,000	0.06	0.06
				10,800	0.14	0.15
				12,000	0.14	0.15
				13,000	0.19	0.20
				14,000	0.22	0.21
				15,000	0.26	0.26
				17,720	Failure	
			Y53	10,450	0.16	0.11
				11,000	0.17	0.12
				12,000	0.21	0.14
				12,900	0.26	0.21
				13,480	0.29	0.22
				14,070	> 0.30	0.25
				14,800	> 0.30	0.28
				15,000	> 0.30	0.30
				15,770	> 0.30	0.33
				16,970	Failure	
Flanged Cap, Flange, LS13116 Lot 2A1	4.0	1.15	X221	71,000	0.10	0.04
				72,000	0.12	0.05
				74,000	0.12	0.06
				75,000	0.14	0.10
				79,000	0.18	0.12
				86,000	> 0.30	0.16
				88,710	Failure	

TABLE 16. - SPECTRUM FATIGUE TEST DATA (Continued)

Shape	K_t	Stress Factor	Specimen	Flights	Crack Length, in (1) L	R
Flanged Cap Flange, LS13116 Lot 2A1	4.0	1.15	X241	160,000	–	0.08
				164,000	–	0.10
				168,000	0.02	0.12
				169,000	0.04	0.14
				171,000	0.06	0.14
				174,000	0.09	0.18
				175,000	0.10	0.18
				179,000	0.15	0.24
				181,700	0.19	0.27
				183,000	0.21	0.30
				184,000	0.22	0.32
				188,000	0.27	0.39
				190,000	0.29	0.40
				192,000	0.29	0.42
				193,300	Failure	
Flanged Cap Flange, LS13116 Lot 2A2	4.0	1.15	Y221	20,000	0.12	0.10
				23,000	0.22	0.21
				24,000	0.24	0.24
				26,720	Failure	
			Y241	100,000	No Failure	

TABLE 17. - SUMMARY OF SPECTRUM FATIGUE TEST DATA

Test Data						Comparison With 7075-T6510 and 7050-T7E 73 (From Ref. 1)			
Shape	Lot	Location	K_t	S.F. (1)	Flights to Failure (2)	Geometric Mean	MA87(CT91) -T7E69(3)	7075-T6510 (3)	7050-T7E73 (3)
Wing Span Cap LS9788 (3)	1A1	Cap	2.7	1.30	16,444	51,340	≥ 43,421	25,494	41,226
			2.7	1.30	38,047				
			2.7	1.30	141,713				
			2.7	1.30	78,360				
	1A2	Cap	2.7	1.30	51,721	≥31,058			
			2.7	1.30	18,650				
Flanged Cap LS13116 (4)	2A1	Base	2.7	1.30	28,360	34,430			
			2.7	1.30	40,500				
		Flange	2.7	1.30	134,330	104,908			
			2.7	1.30	81,930				
	2A2	Base	2.7	1.30	22,480	28,950			
			2.7	1.30	36,360				
		Flange	2.7	1.30	47,800	≥87,453			
			2.7	1.30	160,000 NF				
Wing Spar Cap LS9788 (3)	*1A1*	*Cap*	4.0	1.15	151,000 NF	≥47,516	≥50,254	11,109	14,109
			4.0	1.15	51,270				
			4.0	1.15	22,480				
			4.0	1.15	29,290 GF				
	1A2	Cap	4.0	1.15	100,000 NF	>56,214			
			4.0	1.15	31,600				
Flanged Cap LS13116 (4)	2A1	Base	4.0	1.15	27,750	≥52,678			
			4.0	1.15	100,000 NF				
		Flange	4.0	1.15	88,710	130,949			
			4.0	1.15	193,300				
	2A2	Base	4.0	1.15	17,720	17,341			
			4.0	1.15	16,970				
		Flange	4.0	1.15	26,720	≥51,691			
			4.0	1.15	100,000				

(1) Stress Factor
(2) NF = No Failure and GF = Grip Failure
(3) Specimens machined, etched and chemical film treated, geometric means
(4) Specimens machined only

TABLE 18. - FATIGUE CRACK GROWTH SPECIMEN IDENTIFICATION

Lot	Crack Growth, da/dN Room Temp. Air	Crack Growth, da/dN 3.5% Salt Solution
2A1	Z11 @ 6 Hz Z12 @ 6 Hz Z21 @ 6 Hz	Z13 @ 6 Hz Z14 @ 10 Hz
2A2	Y11 @ 6 Hz Y12 @ 6 Hz	Y13 @ 6 Hz Y14 @ 6 Hz

TABLE 19. - SUMMARY OF FRACTURE TOUGHNESS TEST DATA

Lot	Specimen	Notch Length (in)	a_{s1} (in)	$a_{1/4}$ (in)	$a_{1/2}$ (in)	$a_{3/4}$ (in)	a_{s2}	P_{max} (lbs)	P_Q (lbs)	K_Q ksi$\sqrt{in}$	K_Q MPa$\sqrt{m}$	K_Q=K_{IC}
2A1	X1	0.694	0.1102	0.1502	0.1604	0.1564	0.1007	2540	2540	33.0	36.3	Yes
	X2	0.693	0.1109	0.1308	0.1301	0.1233	0.0949	2560	2560	31.1	34.2	Yes
	X3	0.698	0.0896	0.1242	0.1312	0.1267	0.0942	2580	2580	31.7	34.9	Yes
	X4	0.695	0.0854	0.1188	0.1300	0.1327	0.0976	2600	2600	31.7	34.9	Yes
	X5	0.697	0.0821	0.1154	0.1253	0.1251	0.0942	2620	2620	31.7	34.9	Yes
	X6	0.695	0.0889	0.1538	0.1631	0.1469	0.0980	2330	2330	30.3	33.3	Yes
2A2	Y1	0.692	0.1236	0.1838	0.1864	0.1705	0.1201	2200	2200	30.2	33.2	Yes
	Y2	0.688	0.1683	0.1817	0.1757	0.1833	0.1286	2050	2050	27.9	30.7	Yes
	Y3	0.688	0.1237	0.2097	0.2188	0.2015	0.1271	2100	2100	30.8	33.9	Yes
	Y4	0.688	0.1009	0.1634	0.2210	0.2002	0.0976	2240	2240	31.6	34.8	No (1)
	Y5	0.699	0.1600	0.2549	0.2876	0.2538	0.1650	2120	2120	37.5	41.3	No (1)
	Y6	0.694	0.1200	0.1719	0.1815	0.1712	0.1000	2100	2100	28.6	31.5	Yes

(1) Test Invalid, $a_{si} < 0.9\ a_{avg}$

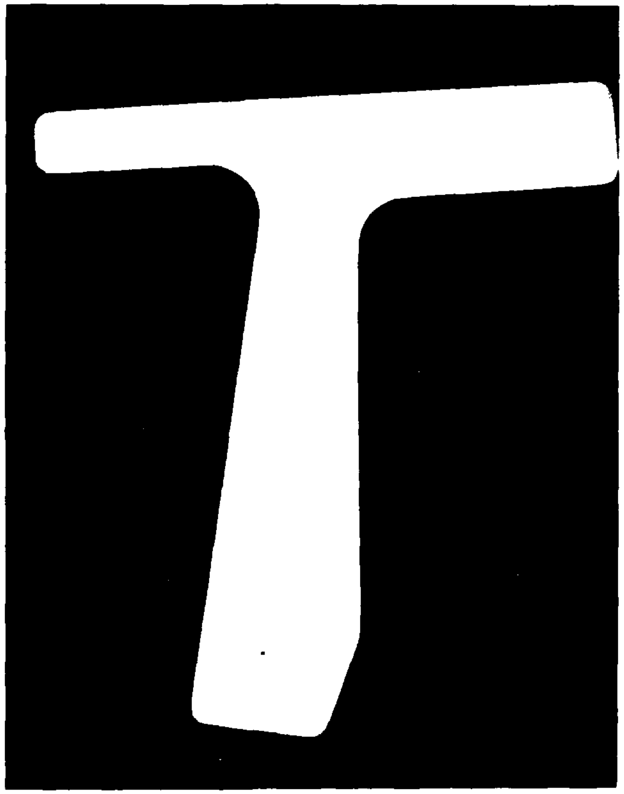


Figure 26. - Cross section of wing spar cap, LS 9788.

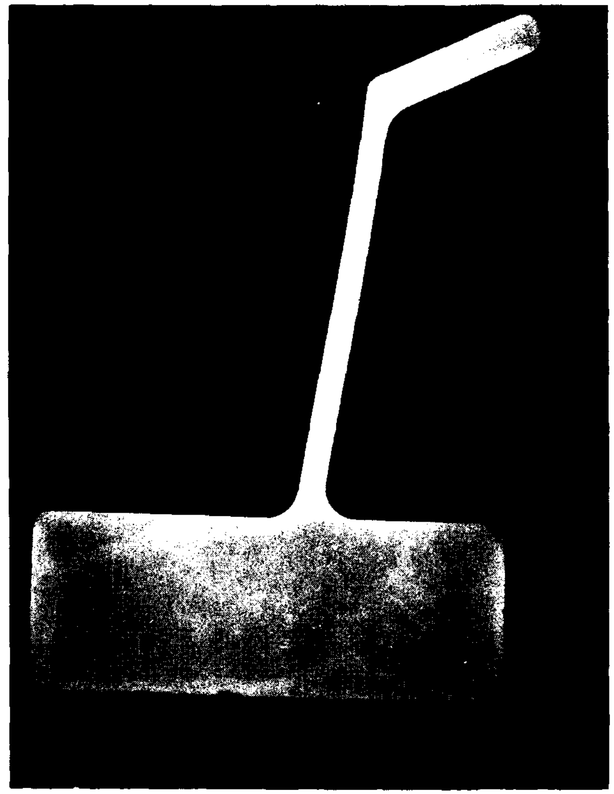
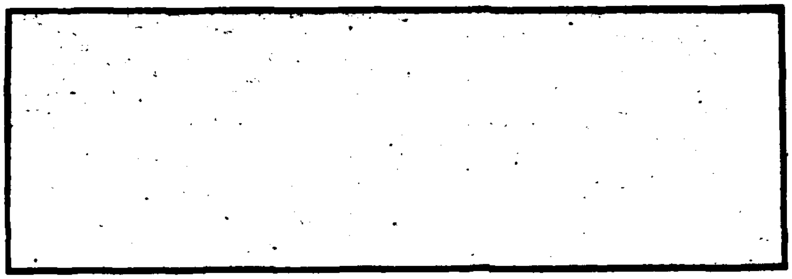
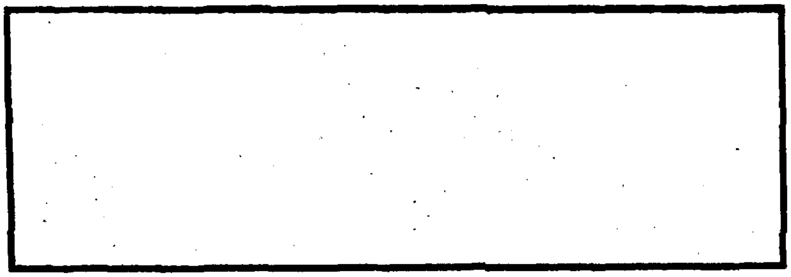


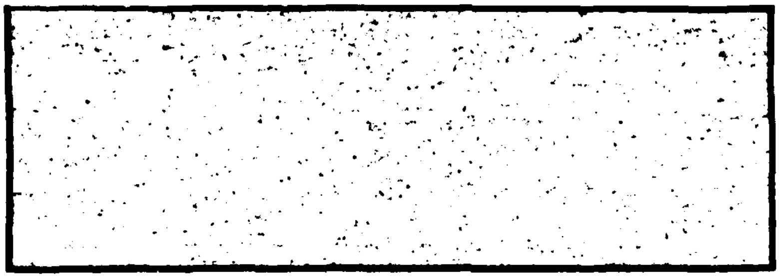
Figure 27. - Cross section of flanged cap, LS 13116.



Longitudinal

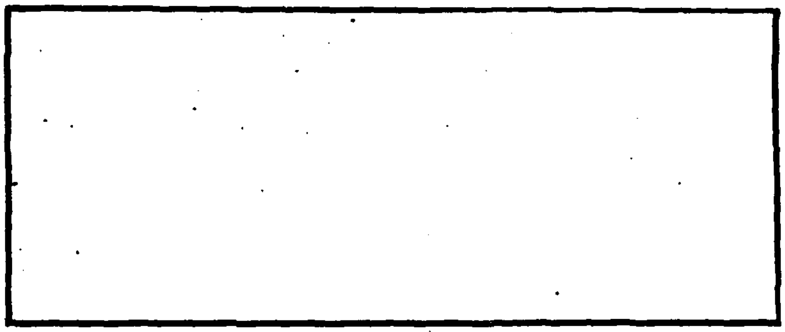


Long Transverse

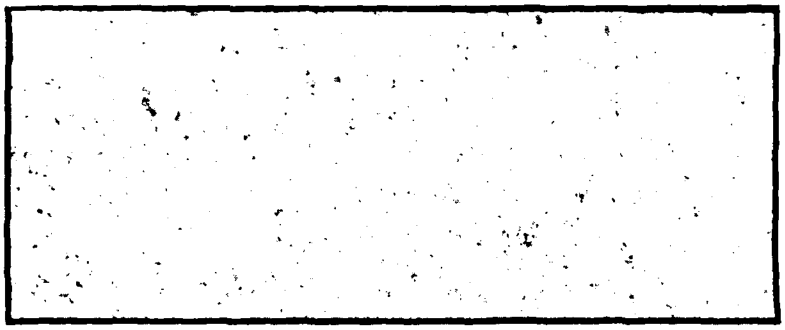


Short Transverse

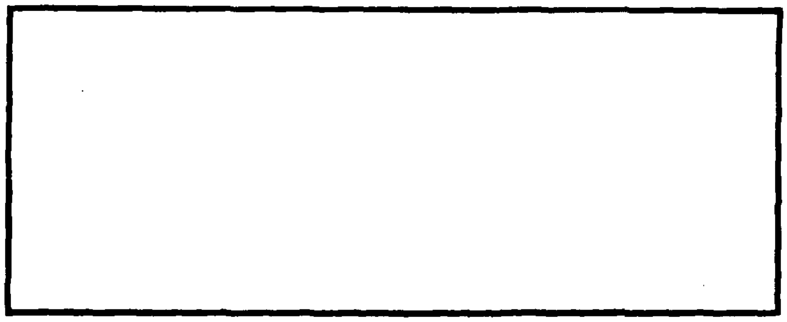
Figure 28. - Photomicrographs of wing spar cap, LS 9788, mag 200x.



Longitudinal



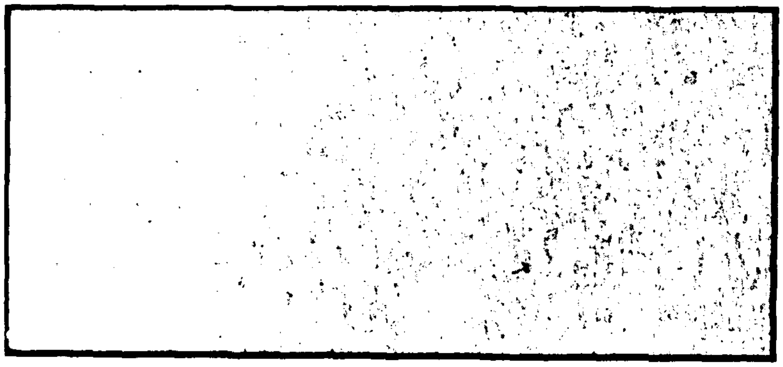
Long Transverse



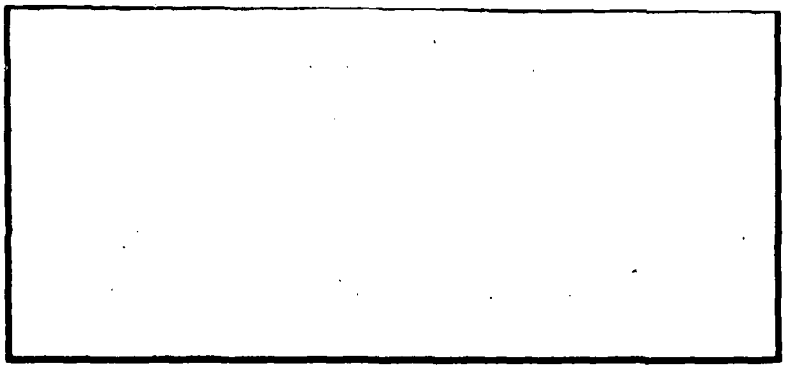
Short Transverse

Figure 29. - Photomicrographs of flanged cap - base, LS 13116, mag 200x.

Longitudinal



Long Transverse



Short Transverse

Figure 30. - Photomicrographs of flanged cap - flange, LS13116 - mag 200x.

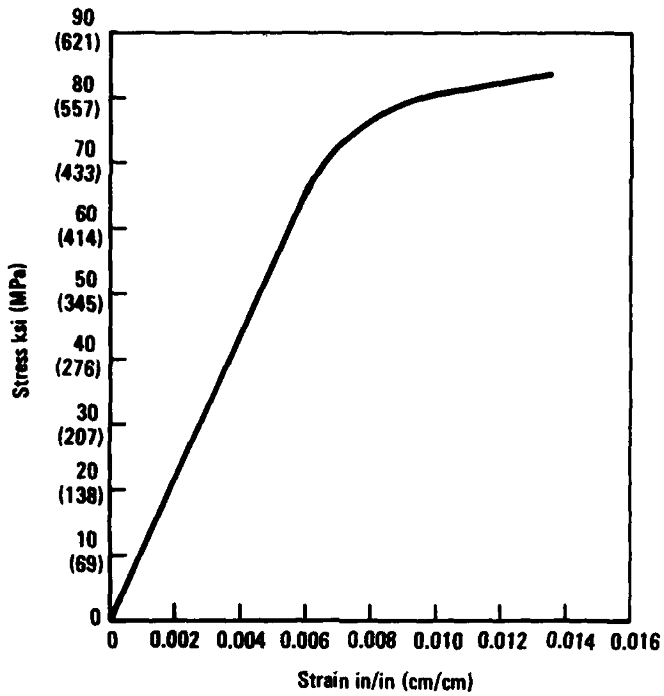


Figure 31. - Typical longitudinal tensile stress - strain curve.

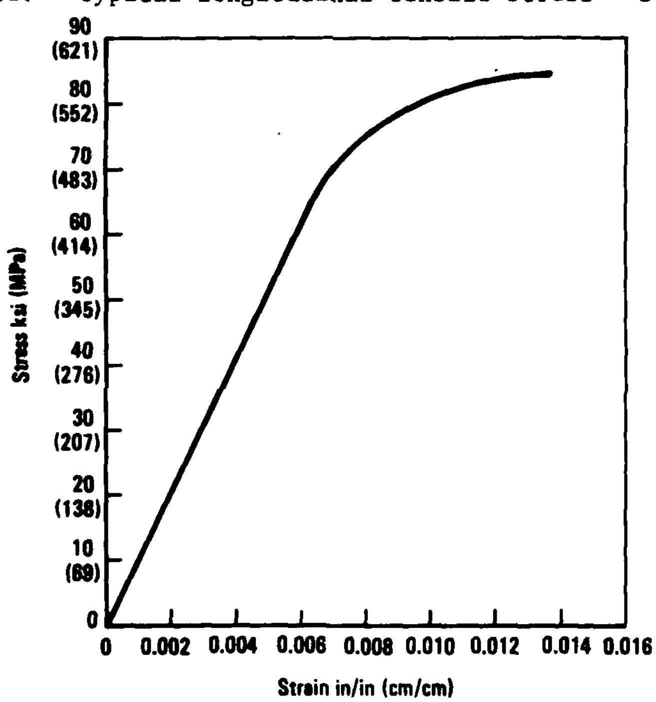
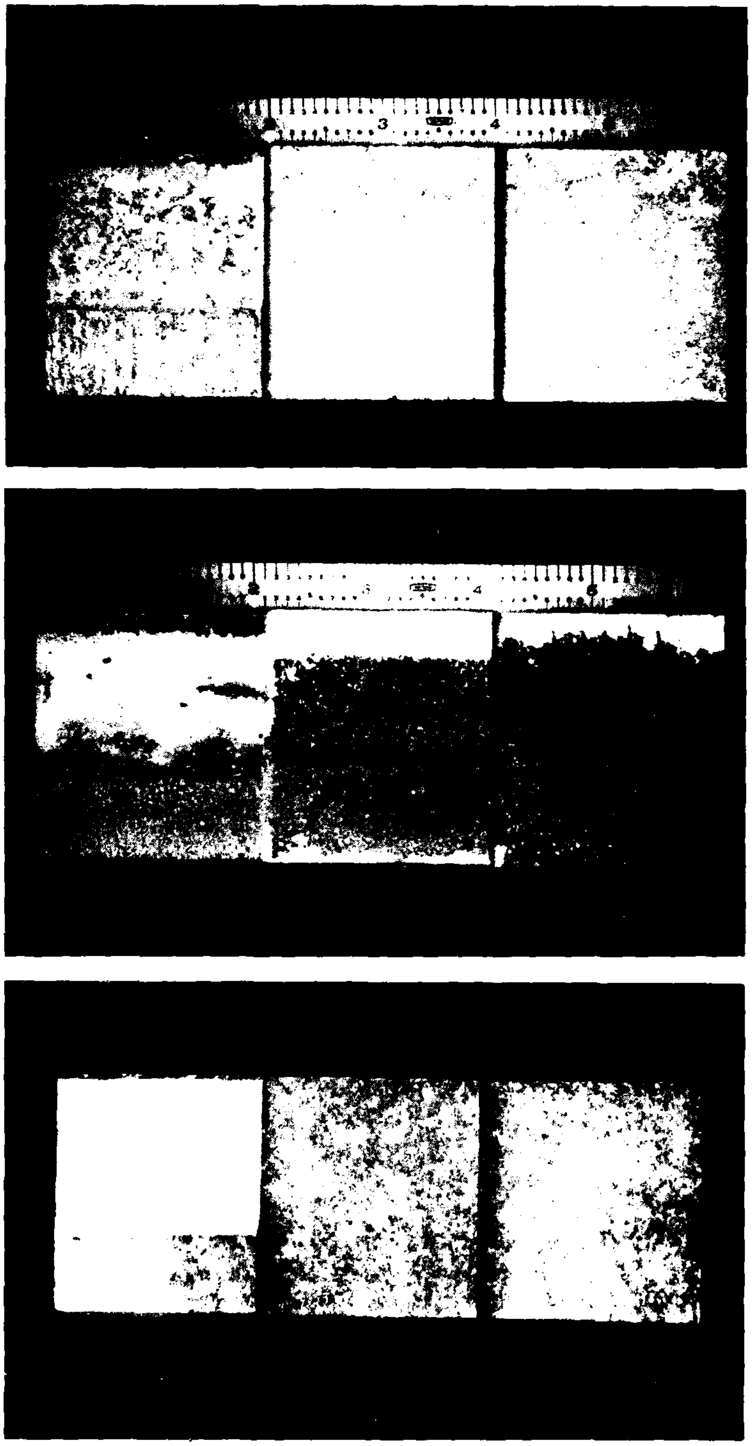


Figure 32. - Typical longitudinal compression stress strain curve.

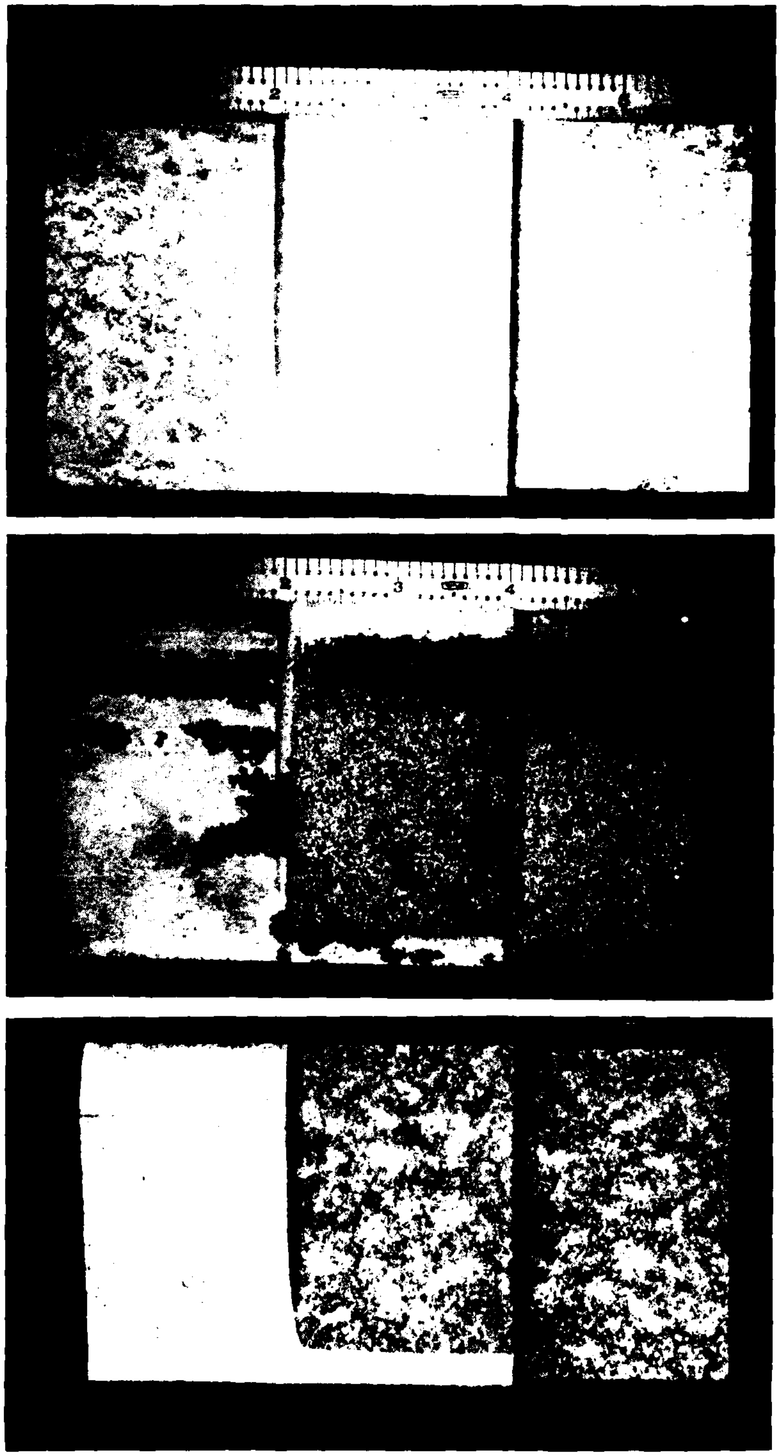


Salt Spray

EXCO

Sea Coast

Figure 33. - Typical surface conditions of wing spar cap - cap, LS 9788 after exfoliation tests.

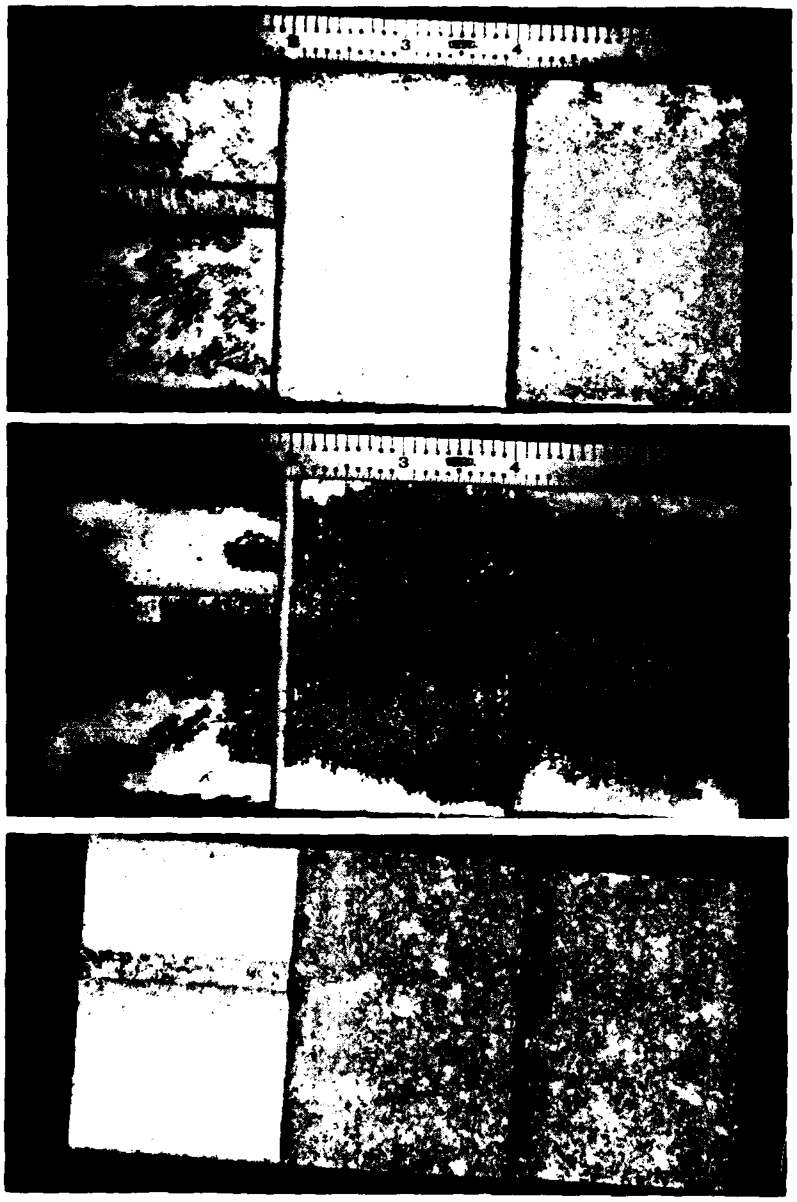


Salt Spray

EXCO

Sea Coast

Figure 34. - Typical surface conditions of wing spar cap - web, LS 9788 after exfoliation tests.

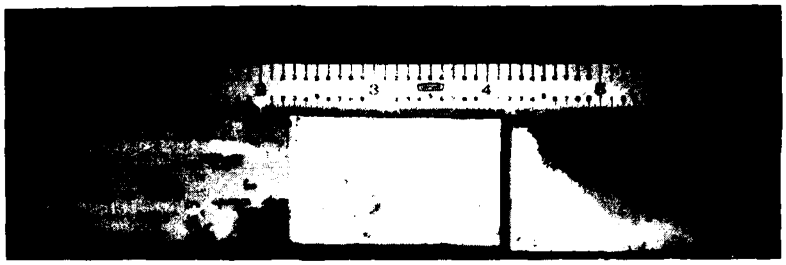


Salt Spray

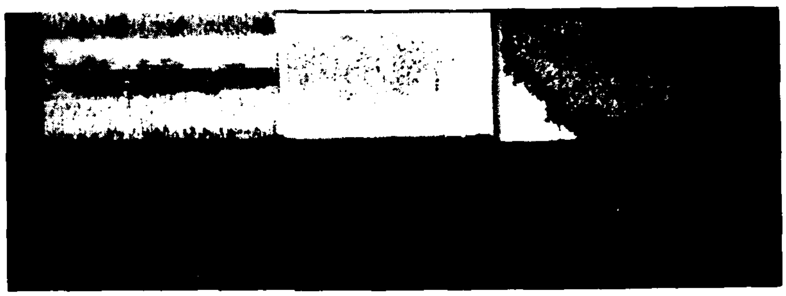
EXCO

Sea Coast

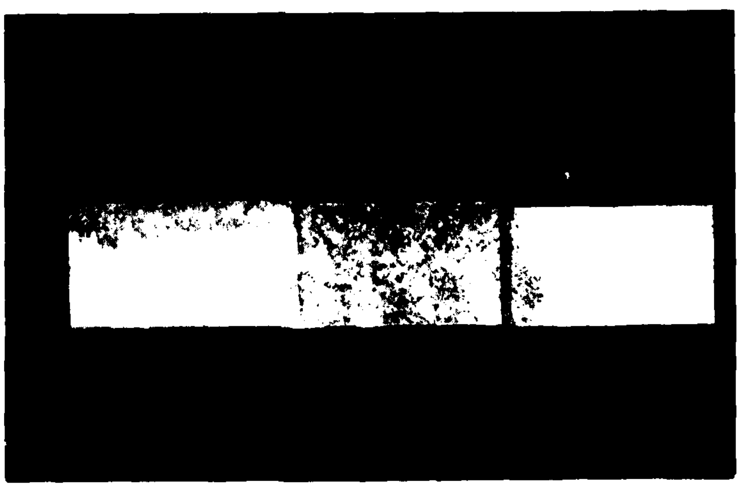
Figure 35. - Typical surface conditions of flanged cap - base, LS 13116 after exfoliation tests.



Salt Spray

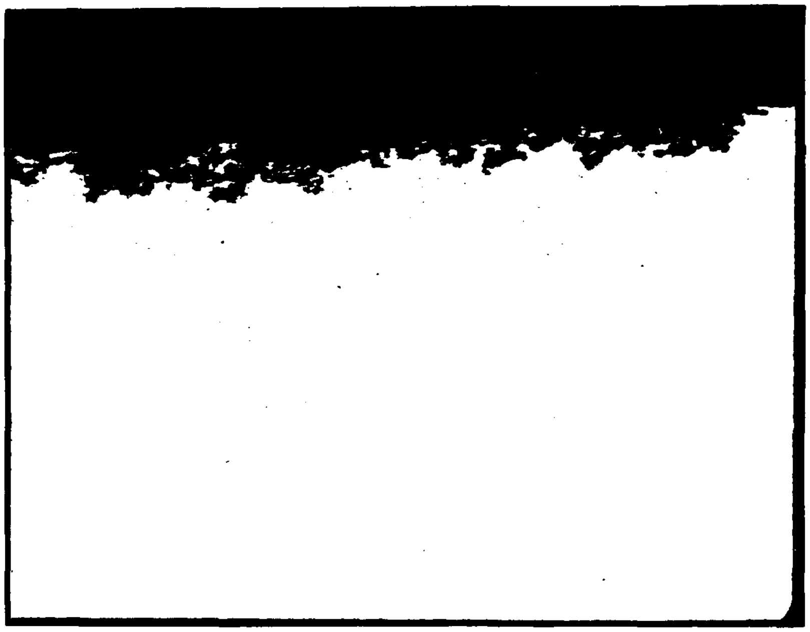


EXCO

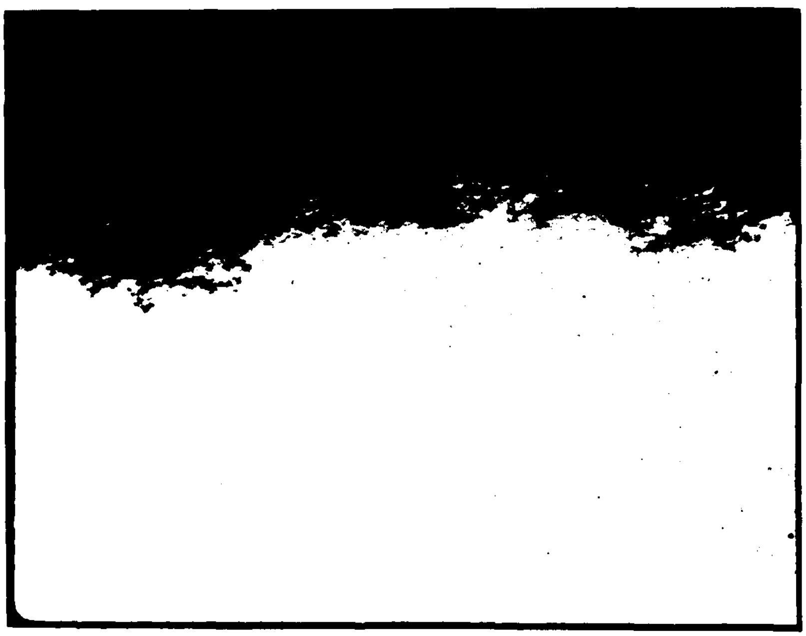


Sea Coast

Figure 36. - Typical surface conditions of flanged cap - flange, LS 13116 after exfoliation tests.



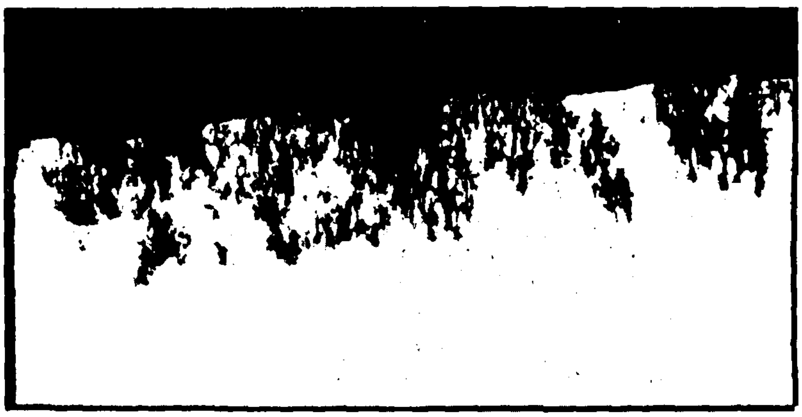
Salt Spray



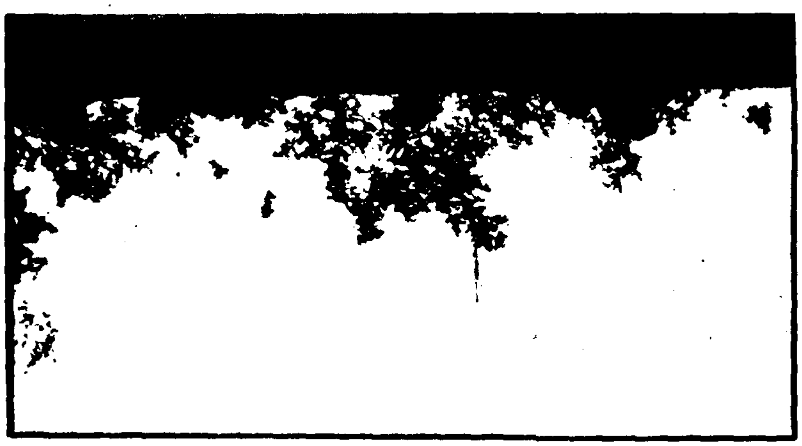
EXCO

Figure 37. - Typical pitting observed after exfoliation testing.

Stressed at 45 ksi
(310 MPa)



Stressed at 35 ksi
(241 MPa)



Stressed at 25 ksi
(172 MPa)

Figure 38. - Photomicrographs of pitted stress corrosion specimens, mag 200x.

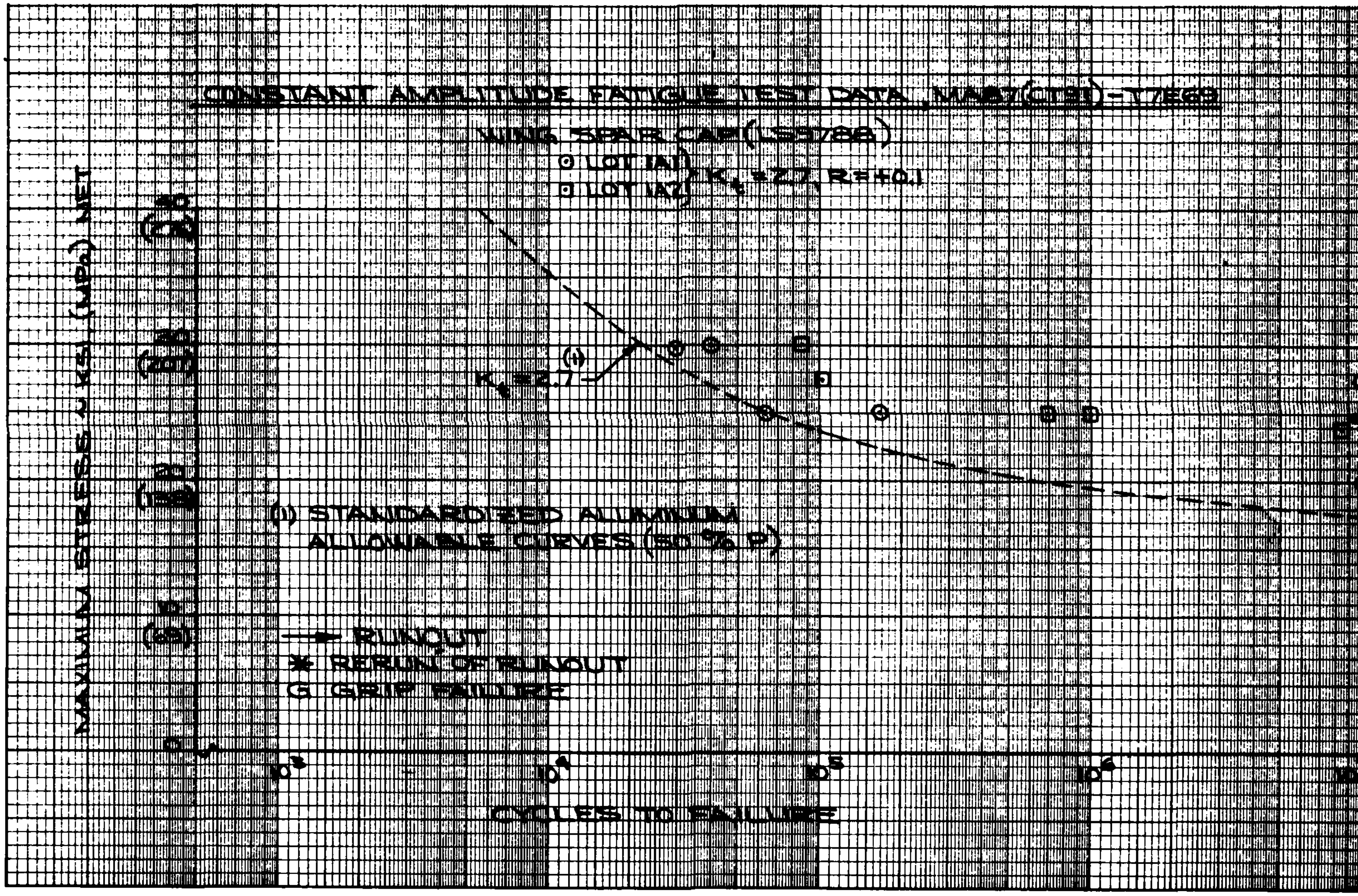


Figure 39. - Constant amplitude fatigue test data, wing spar cap, K_t = 2.7, R = 0.1.

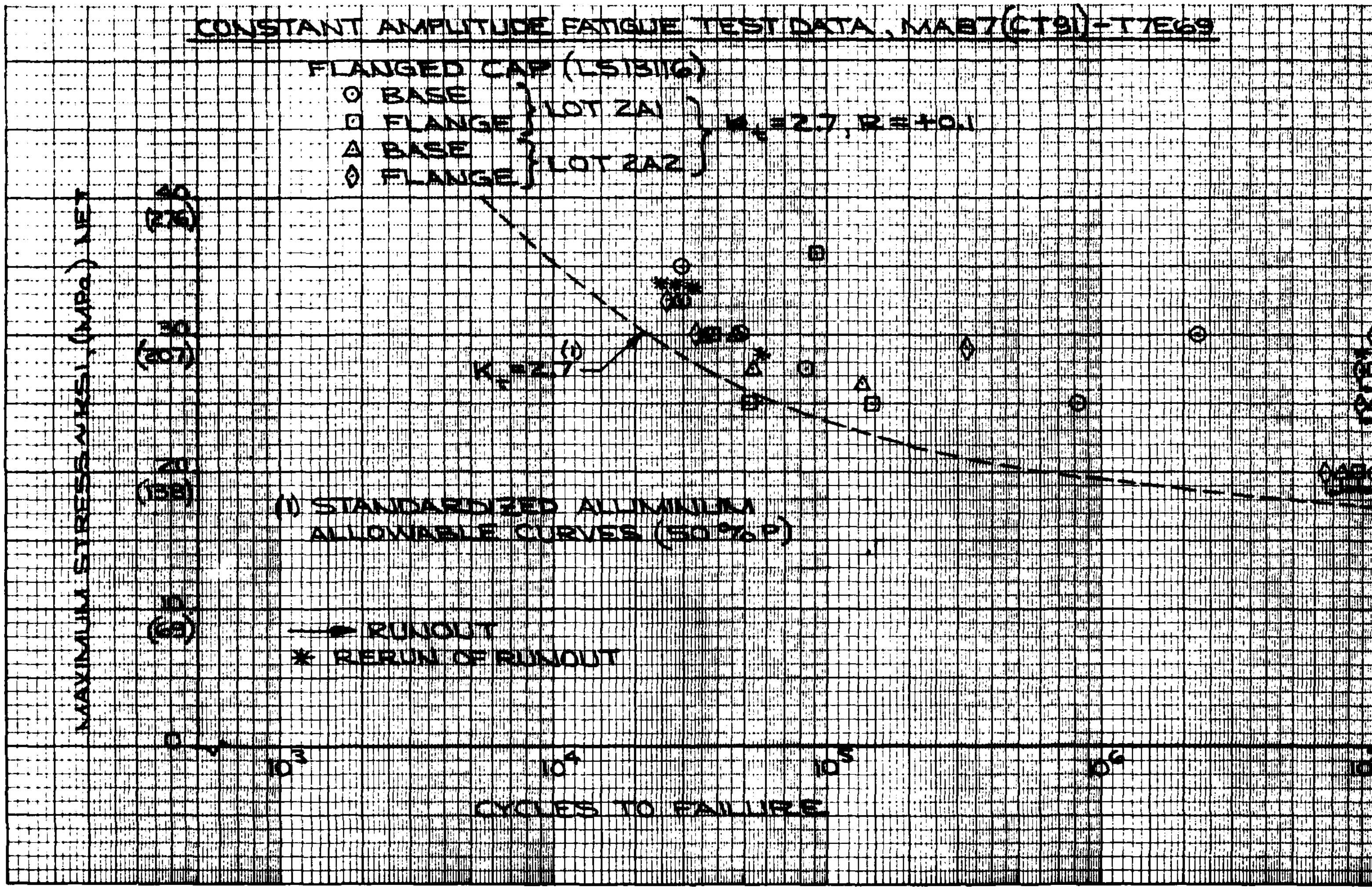


Figure 40. - Constant amplitude fatigue test data, flanged cap, $K_t = 2.7$, $R = 0.1$.

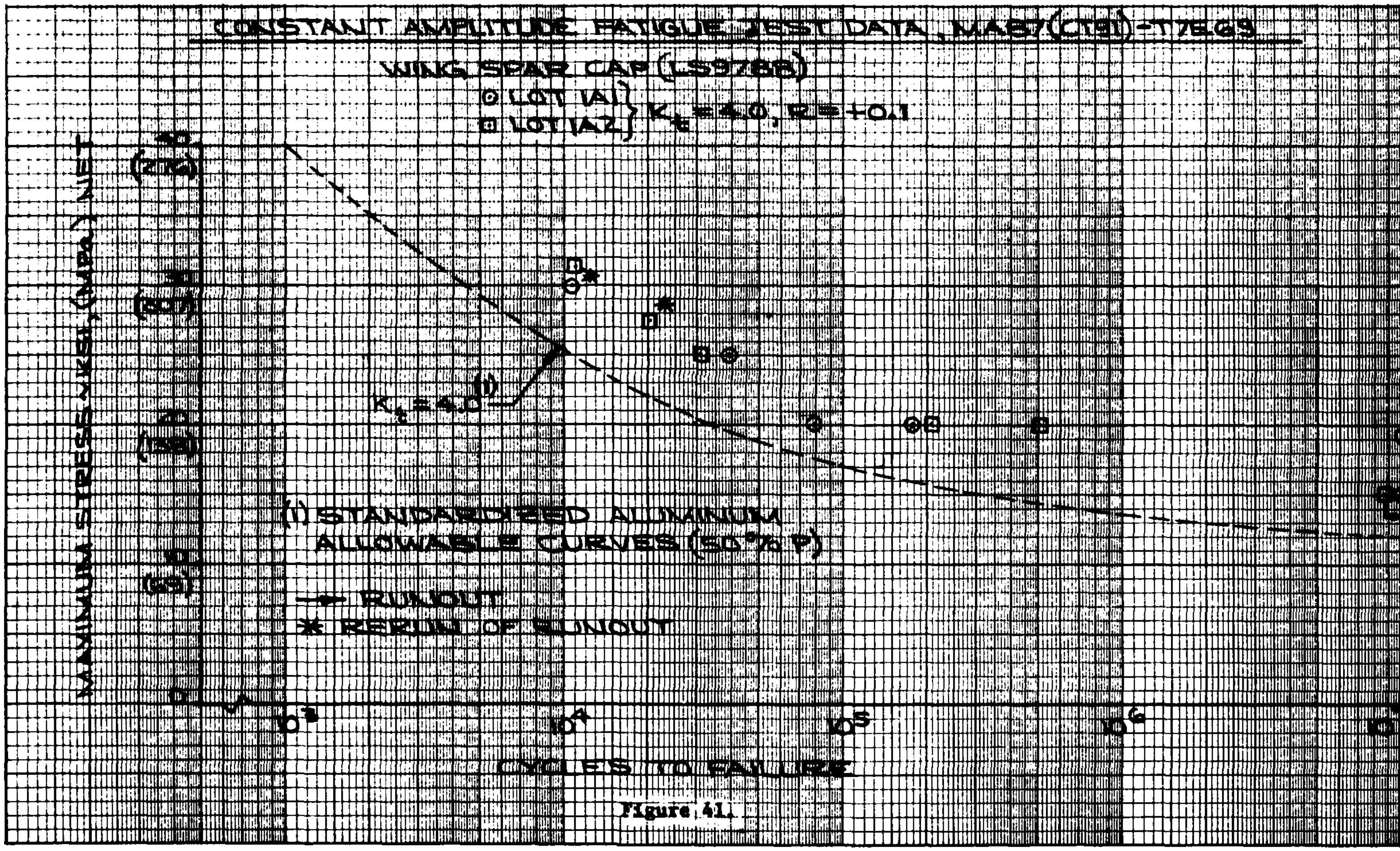


Figure 41. - Constant amplitude fatigue test data, wing spar cap, K_t = 4.0, R = 0.1.

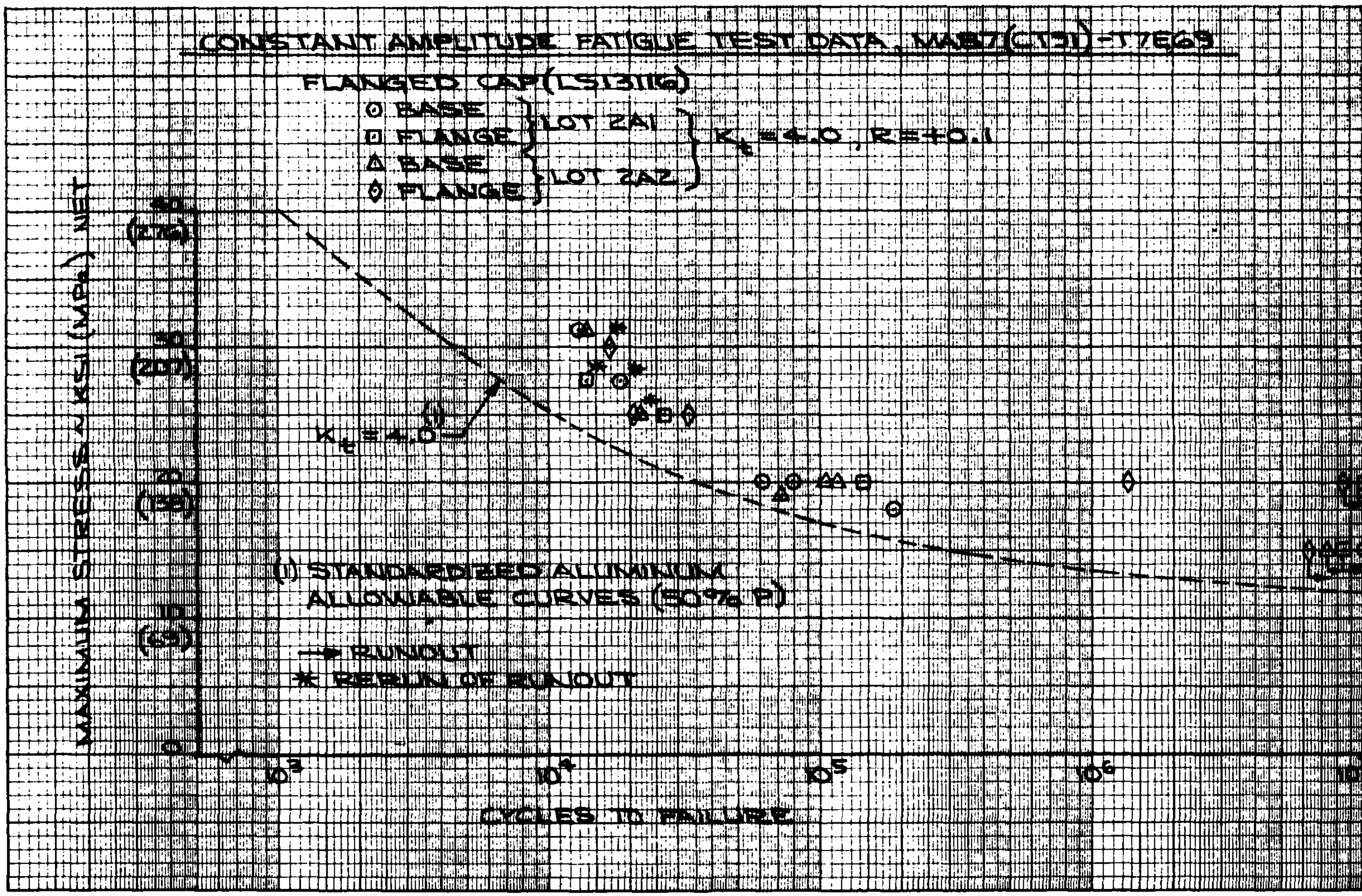


Figure 42. - Constant amplitude fatigue test data, flanged cap, K_t = 4.0, R = 0.1.

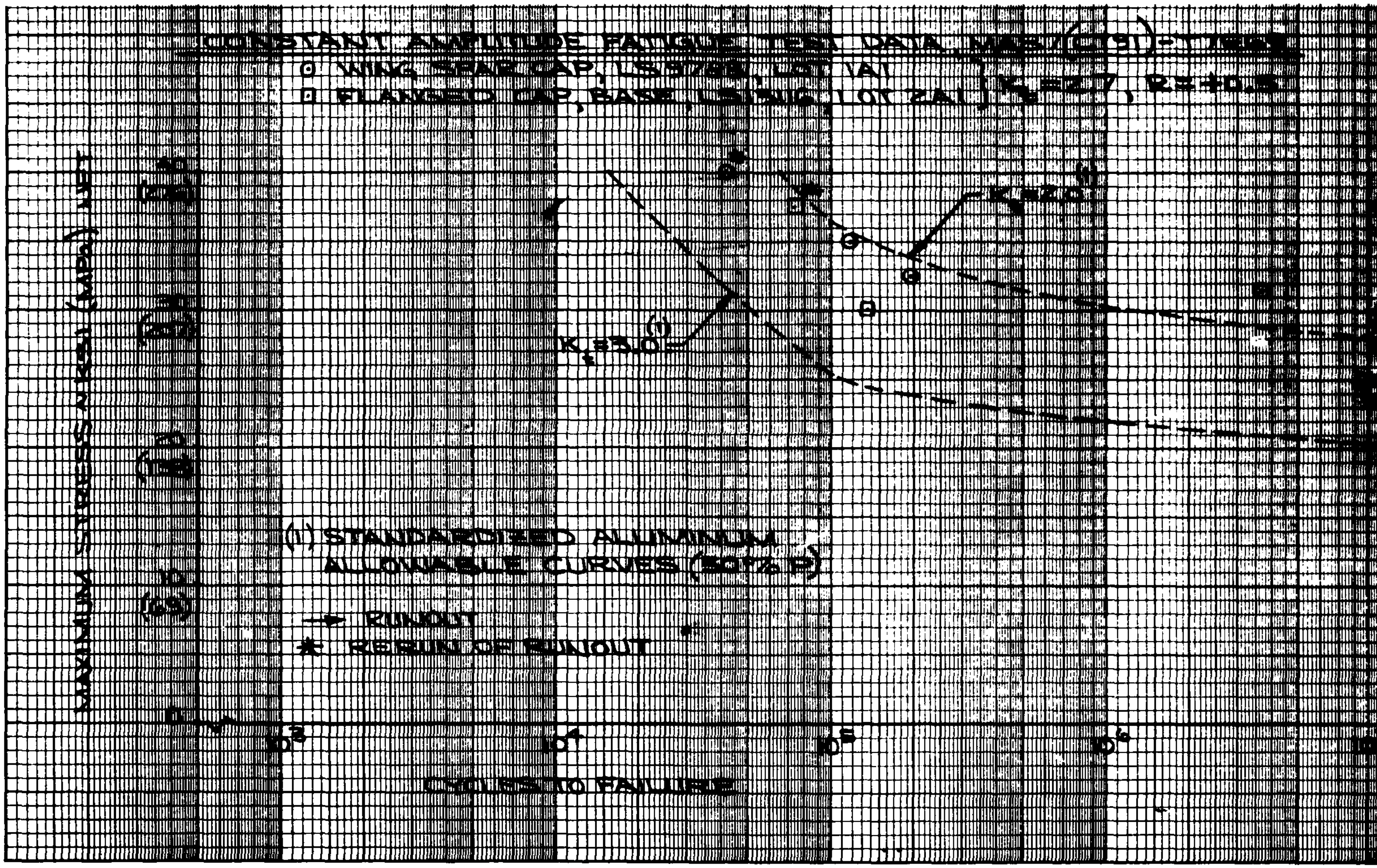


Figure 43. - Constant amplitude fatigue test data, wing spar cap and flanged cap, K_t = 2.7, R = 0.5.

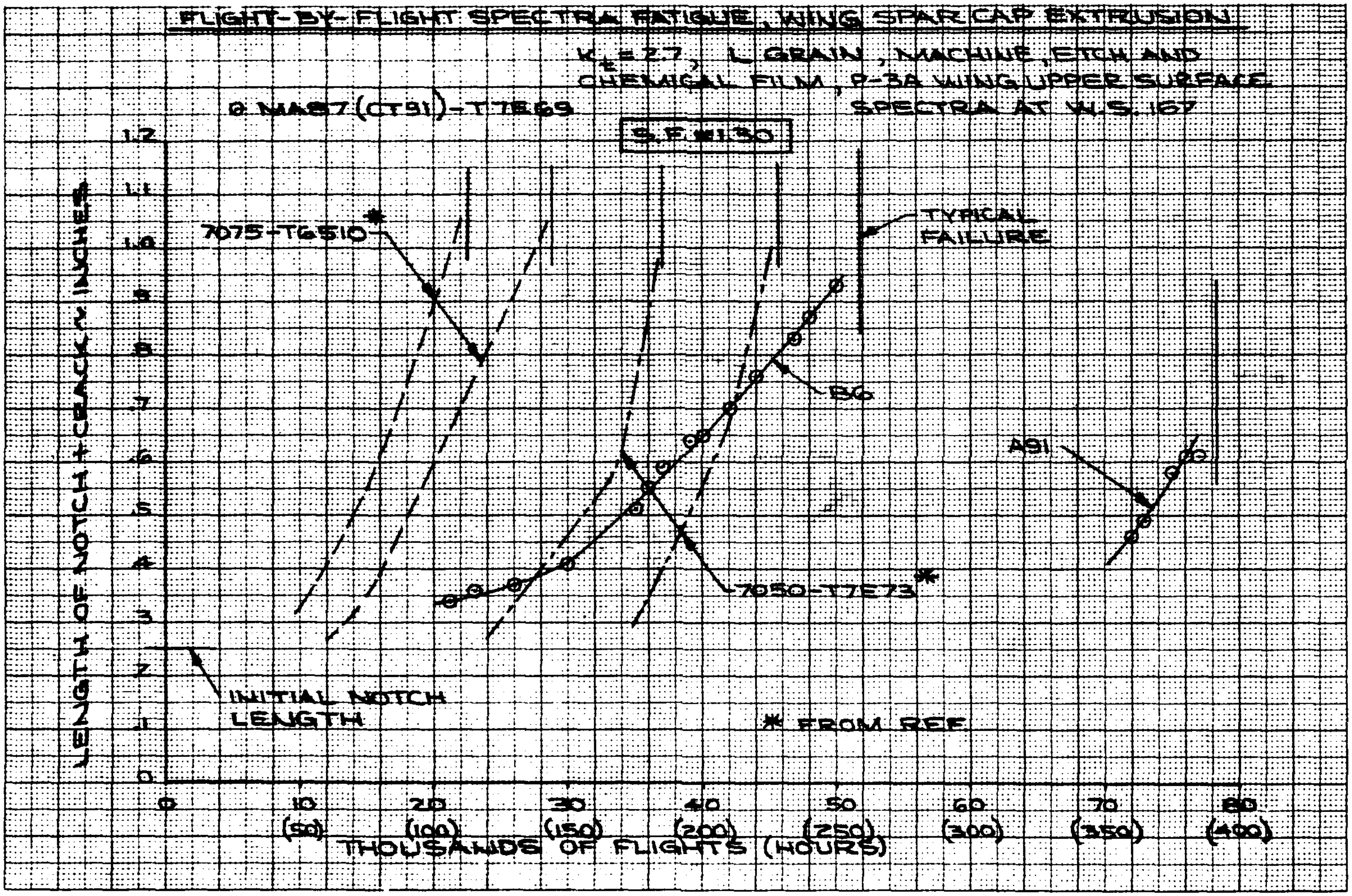


Figure 44. - Comparison of MA87(CT91)-T7E69, 7075-T6510, and 7050-T7E73 wing spar cap spectrum fatigue, K_t = 2.7

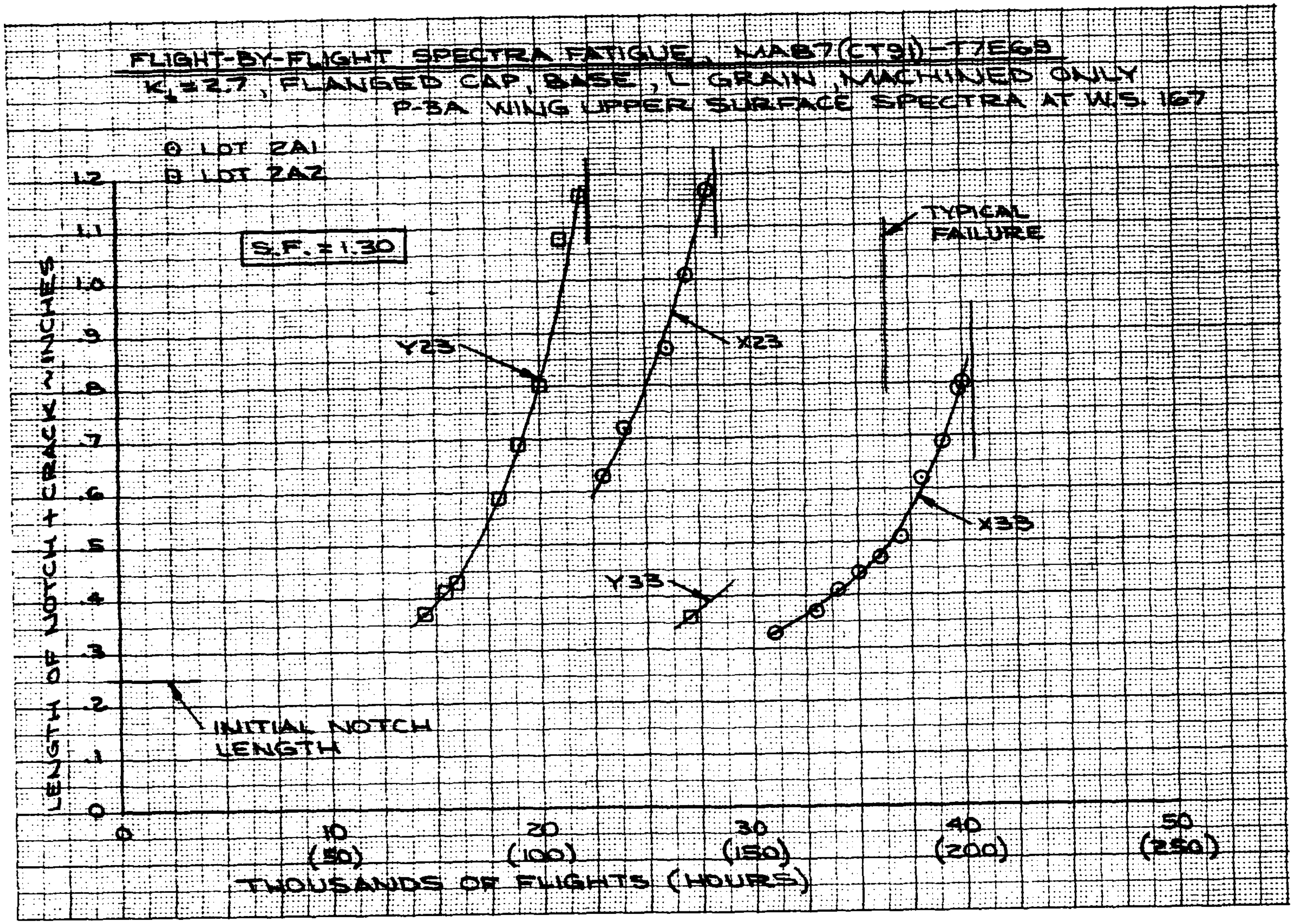


Figure 45. - Spectrum fatigue of flanged cap - base specimens K_t = 2.7.

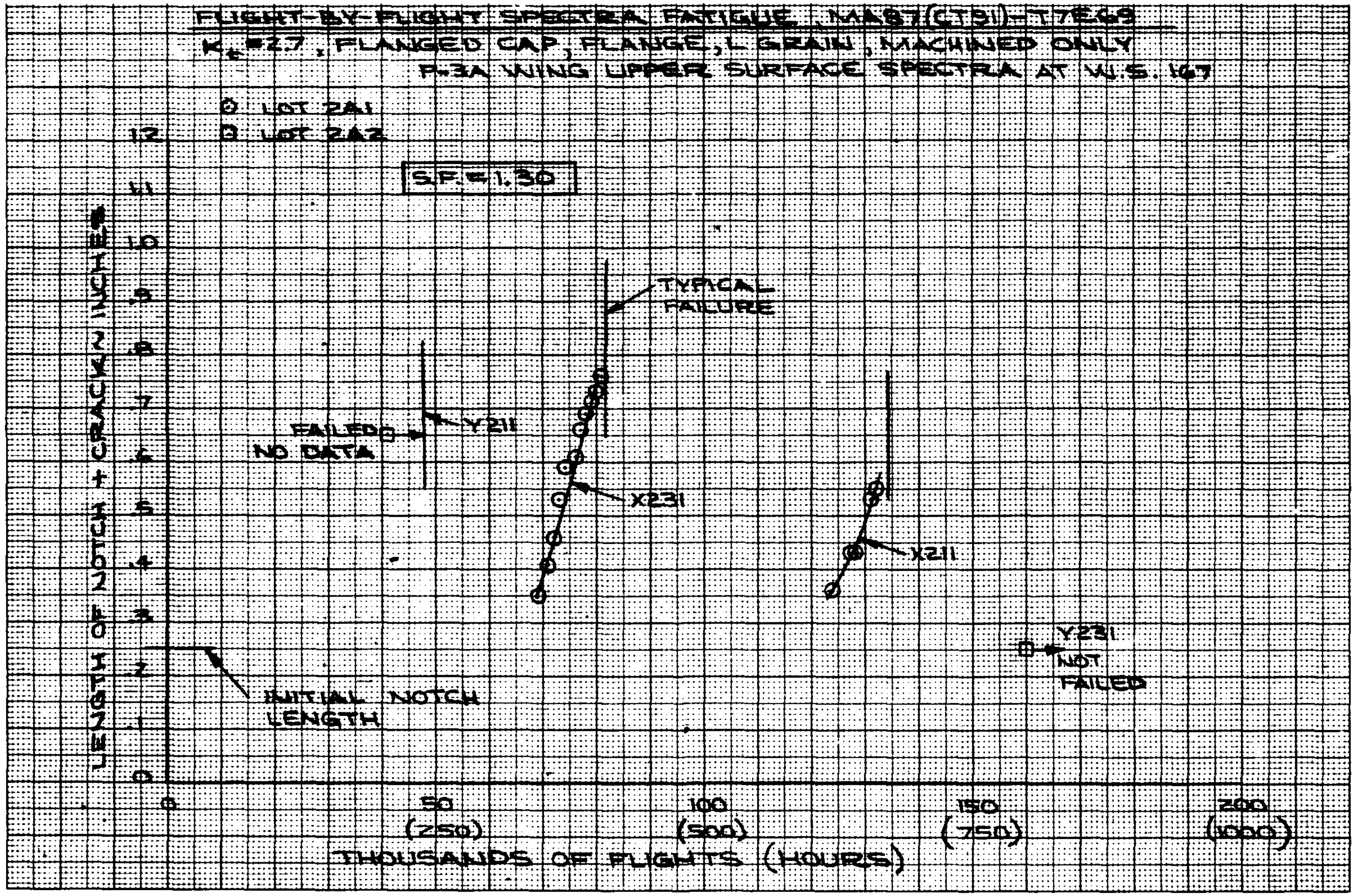


Figure 46. - Spectrum fatigue of flange cap - flange specimens K_t = 2.7.

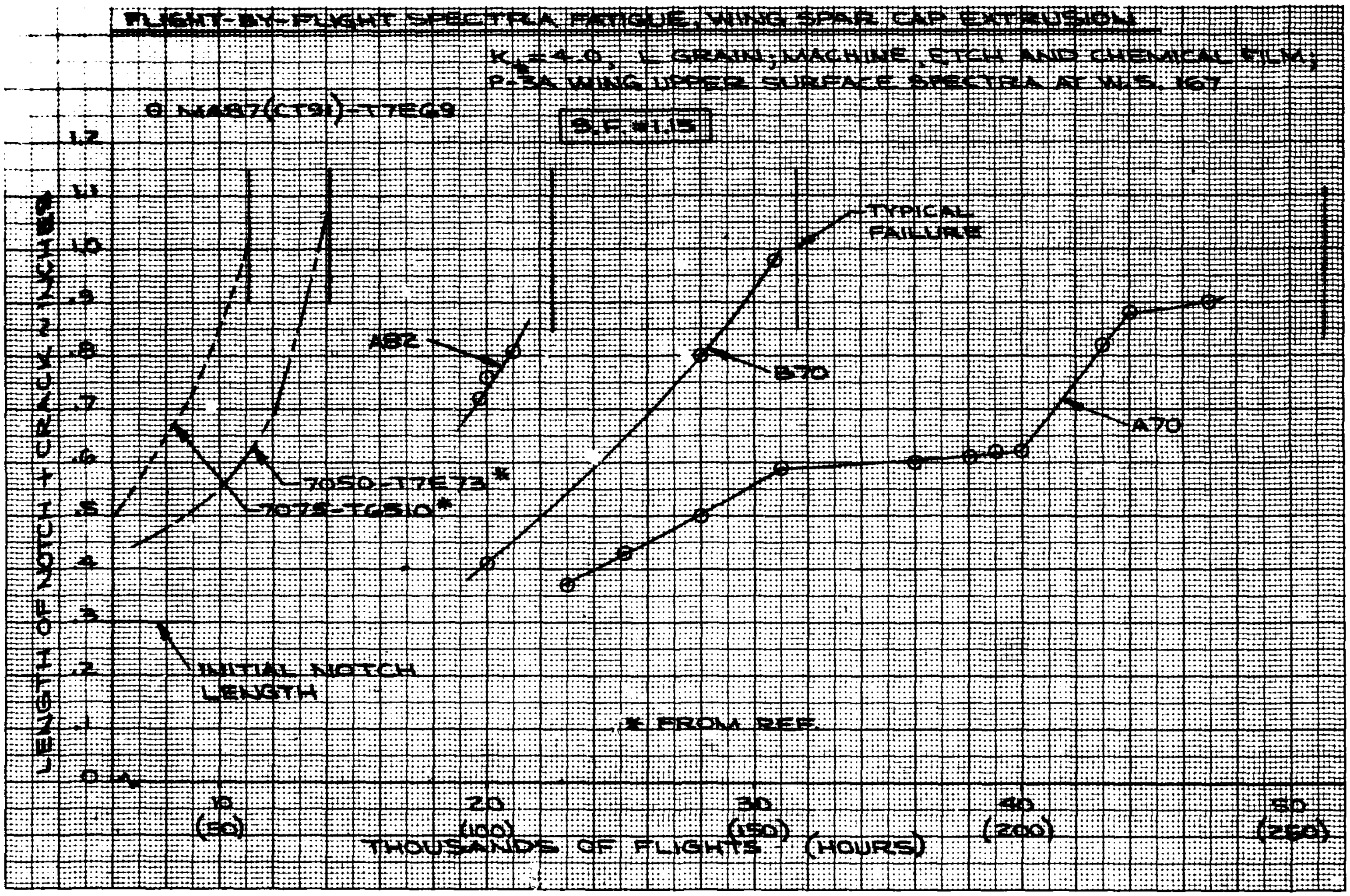


Figure 47. - Comparison of MA87(CT91)-T7E69, 7075-T6510 and 7050-T7E73 wing spar cap spectrum fatigue, K_t = 4.0

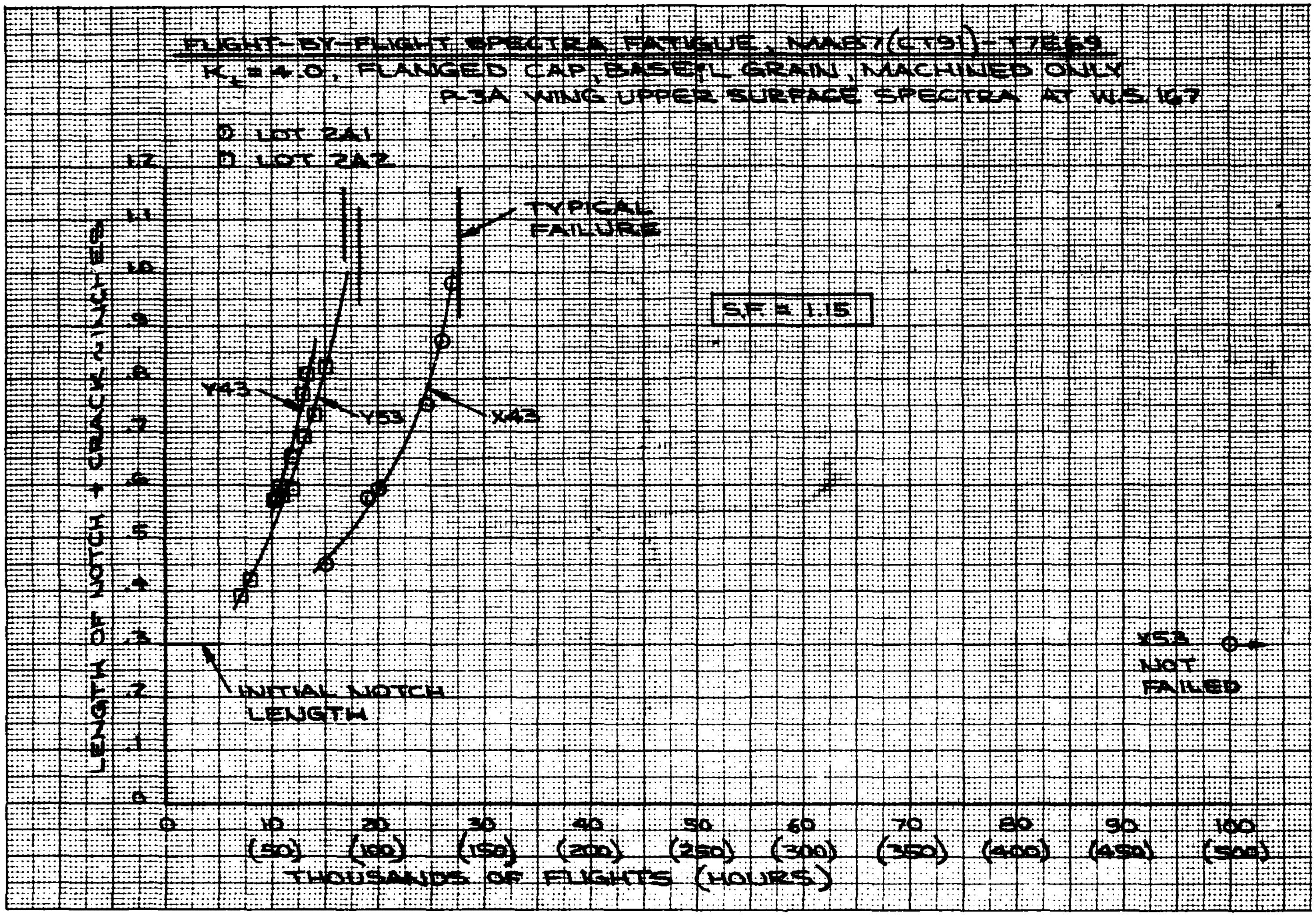


Figure 48. - Spectrum fatigue of flanged cap - base specimens K_t = 4.0.

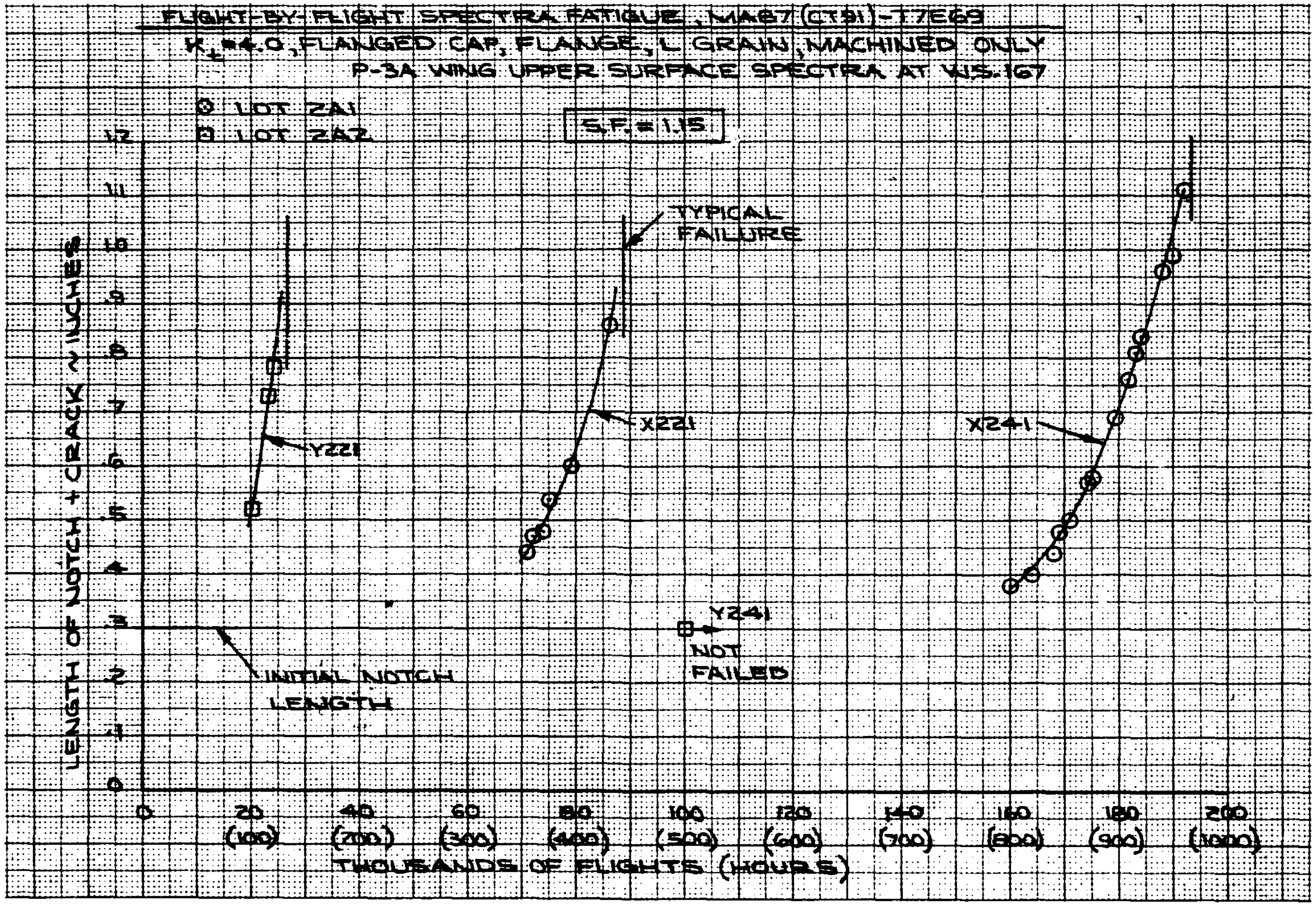


Figure 49. - Spectrum fatigue of flanged cap - flange specimens, $K_t = 4.0$.

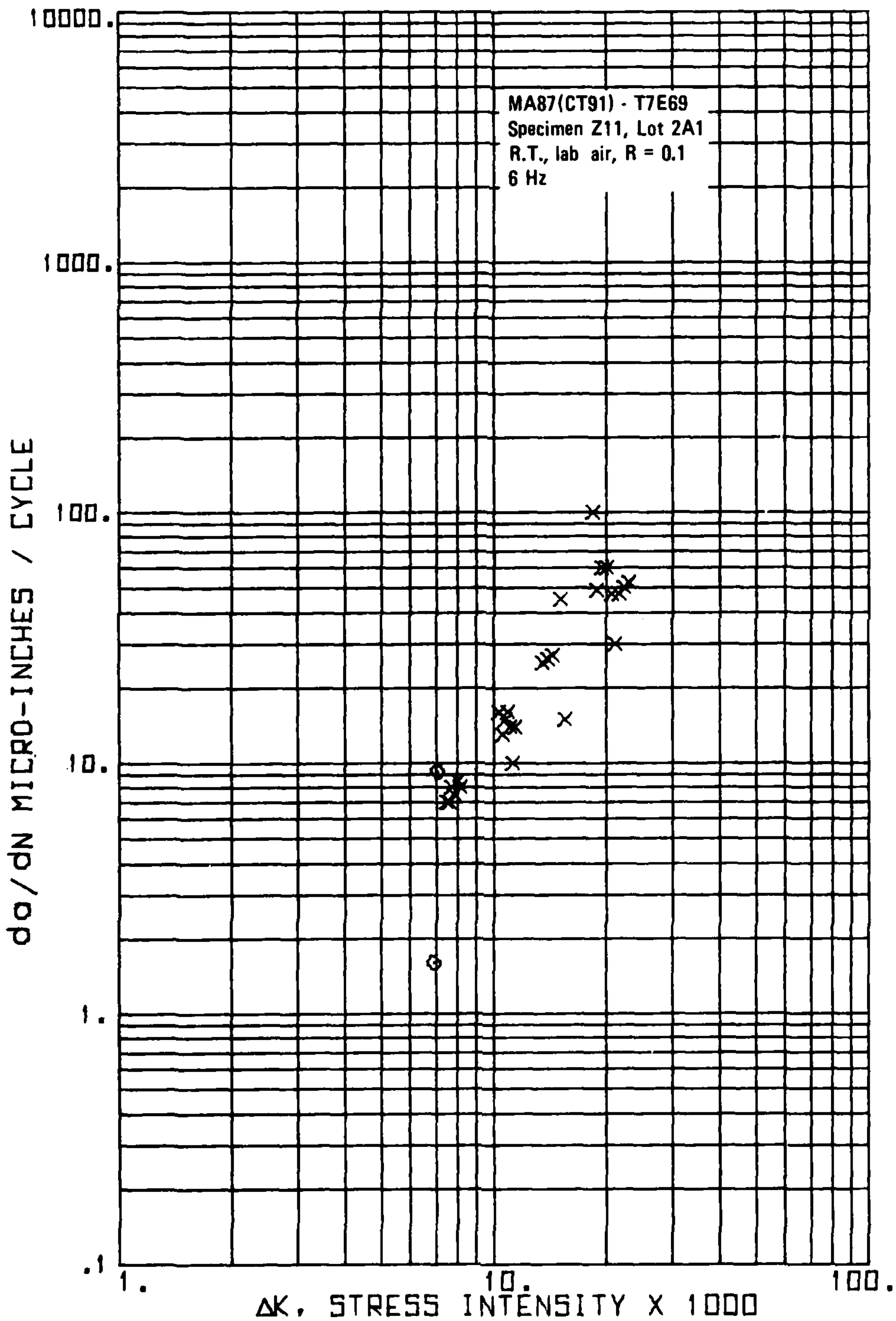


Figure 50. - Fatigue crack growth of specimen Z11, lot 2A1 in lab air.

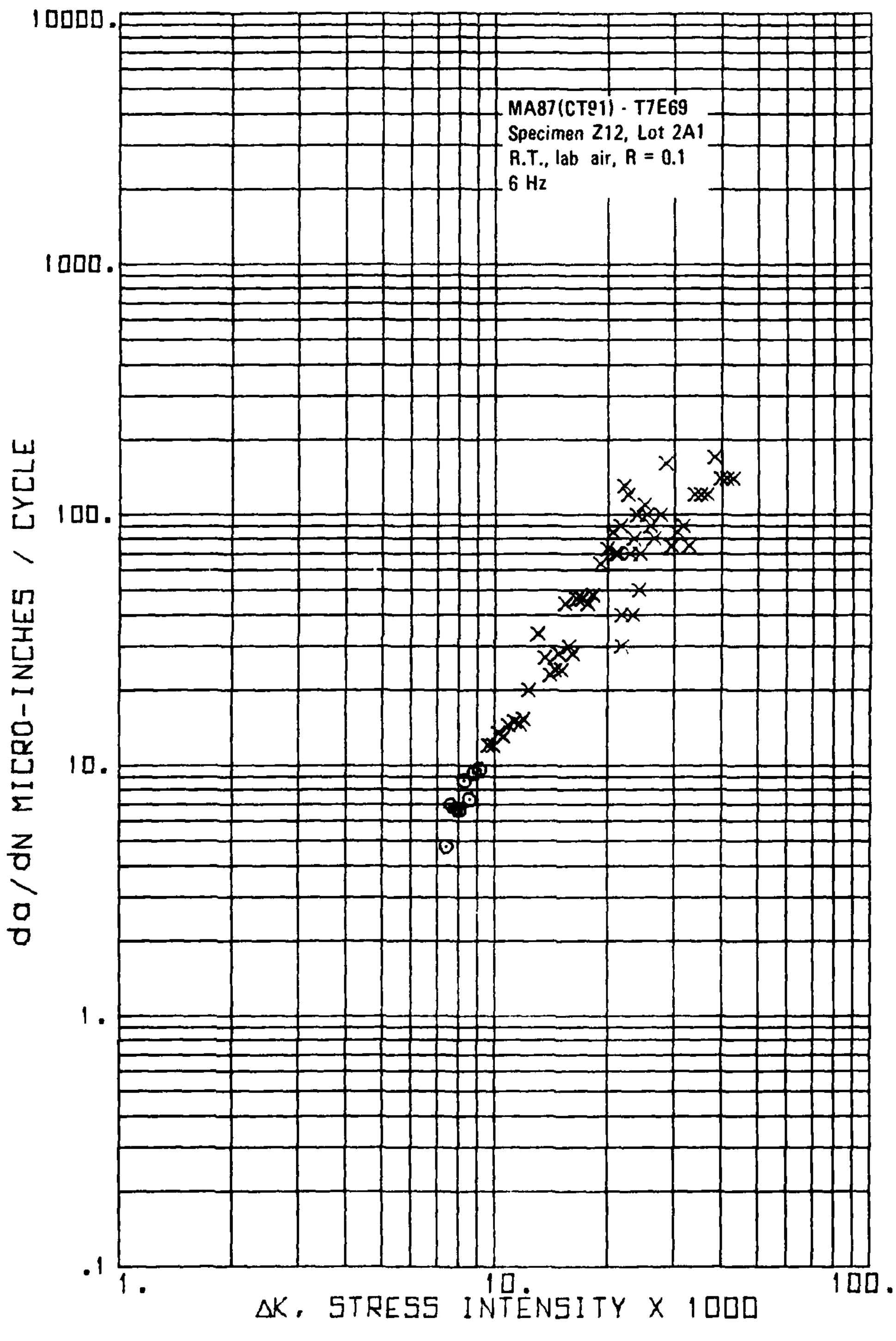


Figure 51. - Fatigue crack growth of specimen Z12, lot 2A1 in lab air.

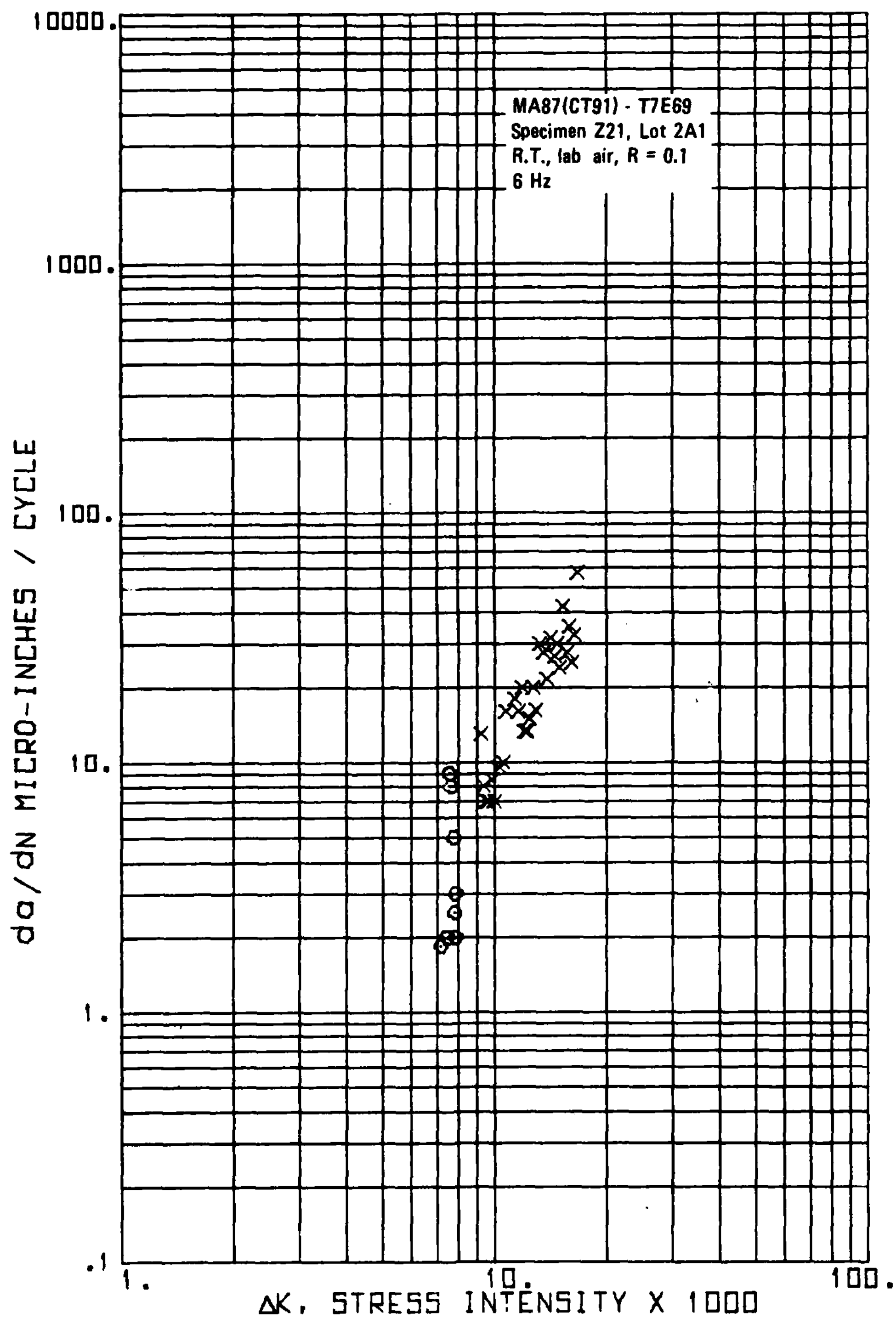


Figure 52. - Fatigue crack growth of specimen Z21, lot 2A1 in lab air.

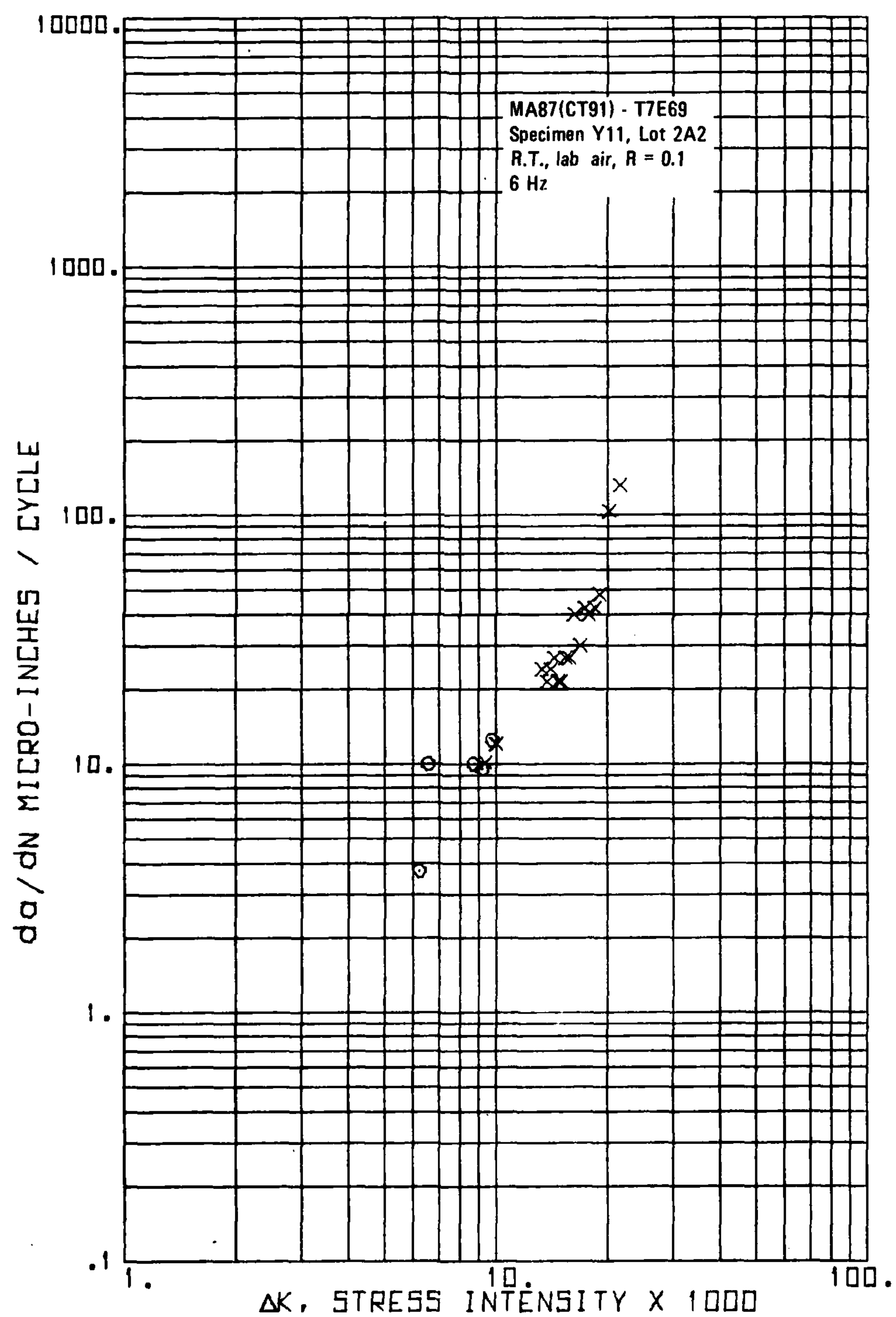


Figure 53. - Fatigue crack growth of specimen Y11, lot 2A2 in lab air.

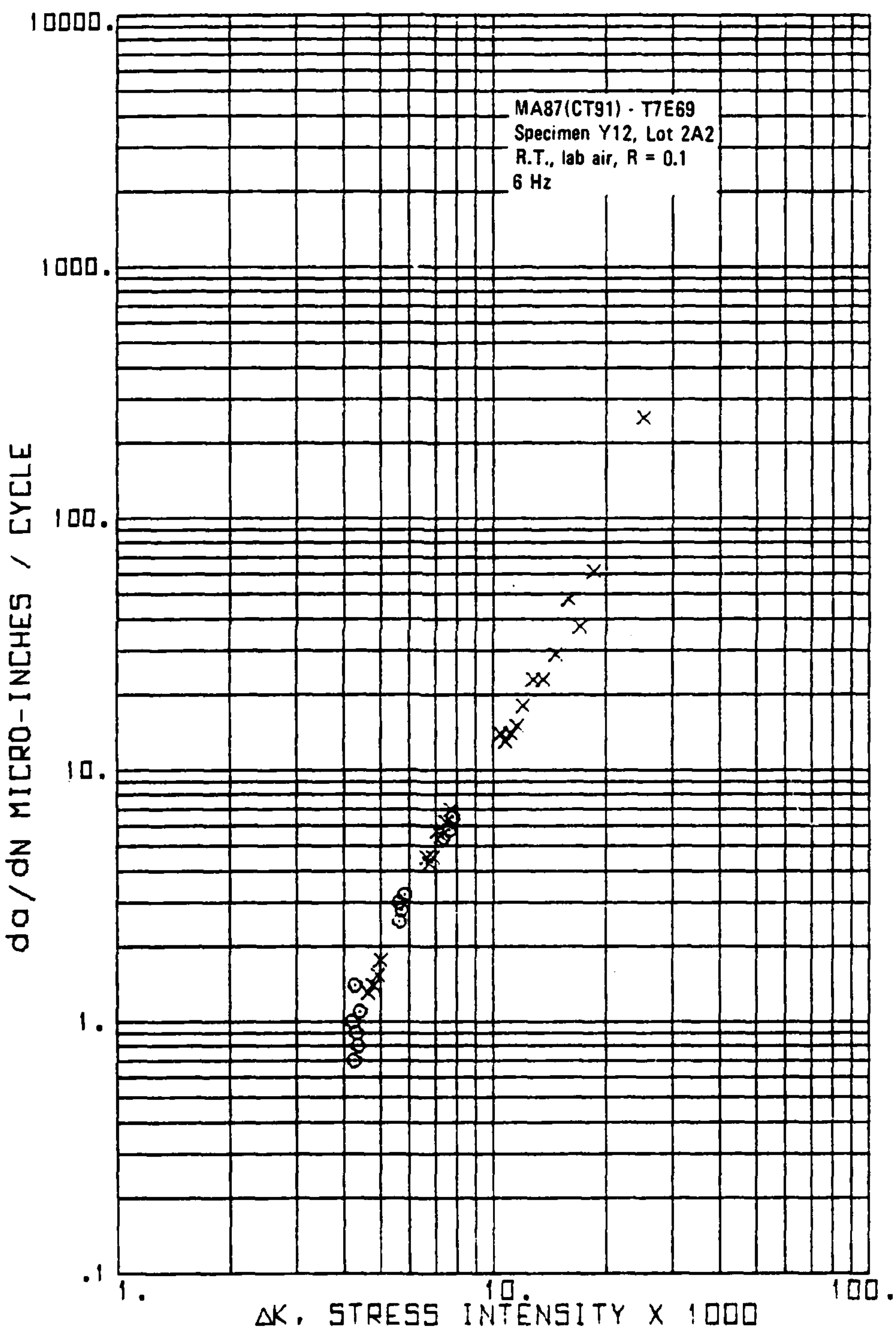


Figure 54. - Fatigue crack growth of specimen Y12, lot 2A2 in lab air.

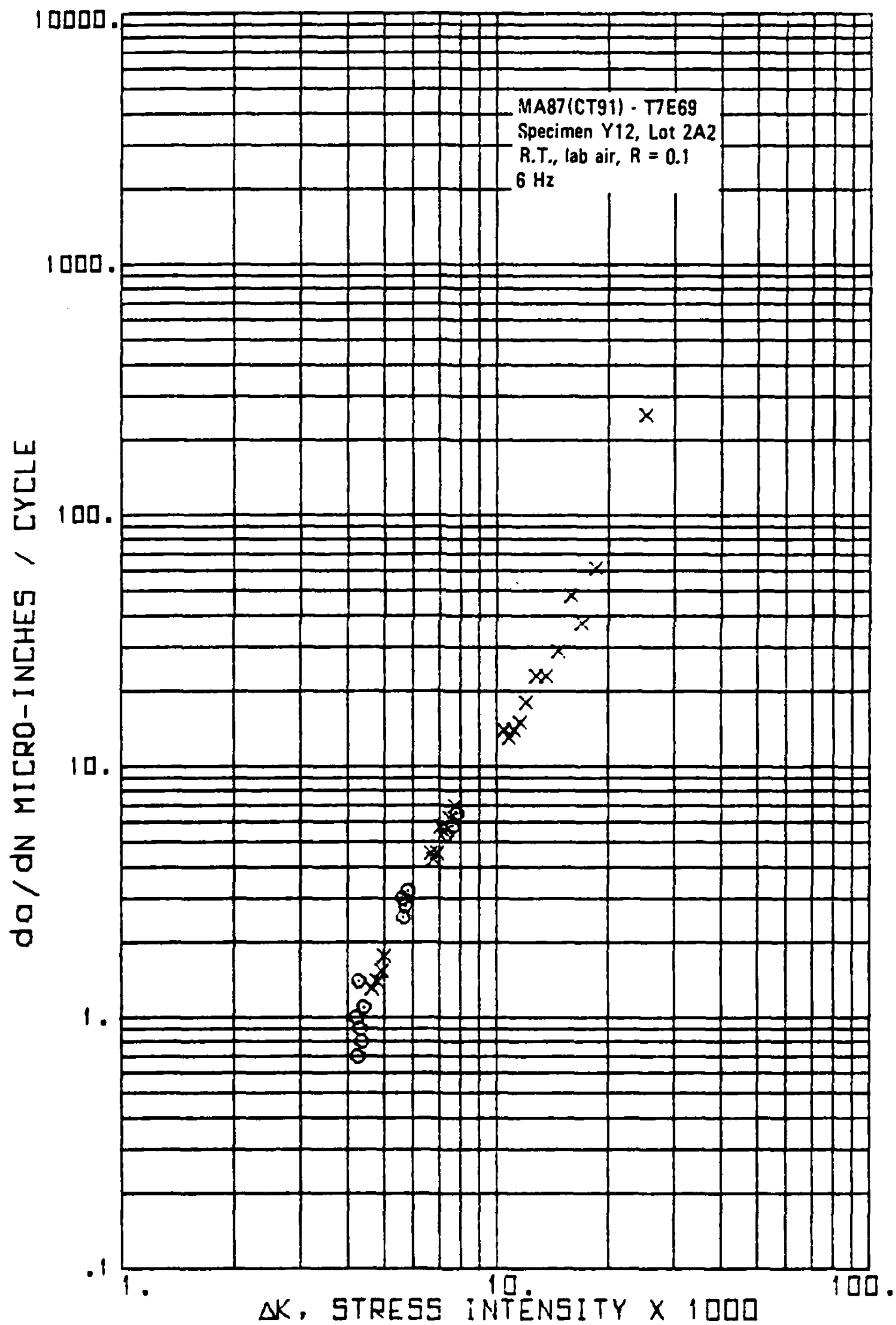


Figure 54. - Fatigue crack growth of specimen Y12, lot 2A2 in lab air.

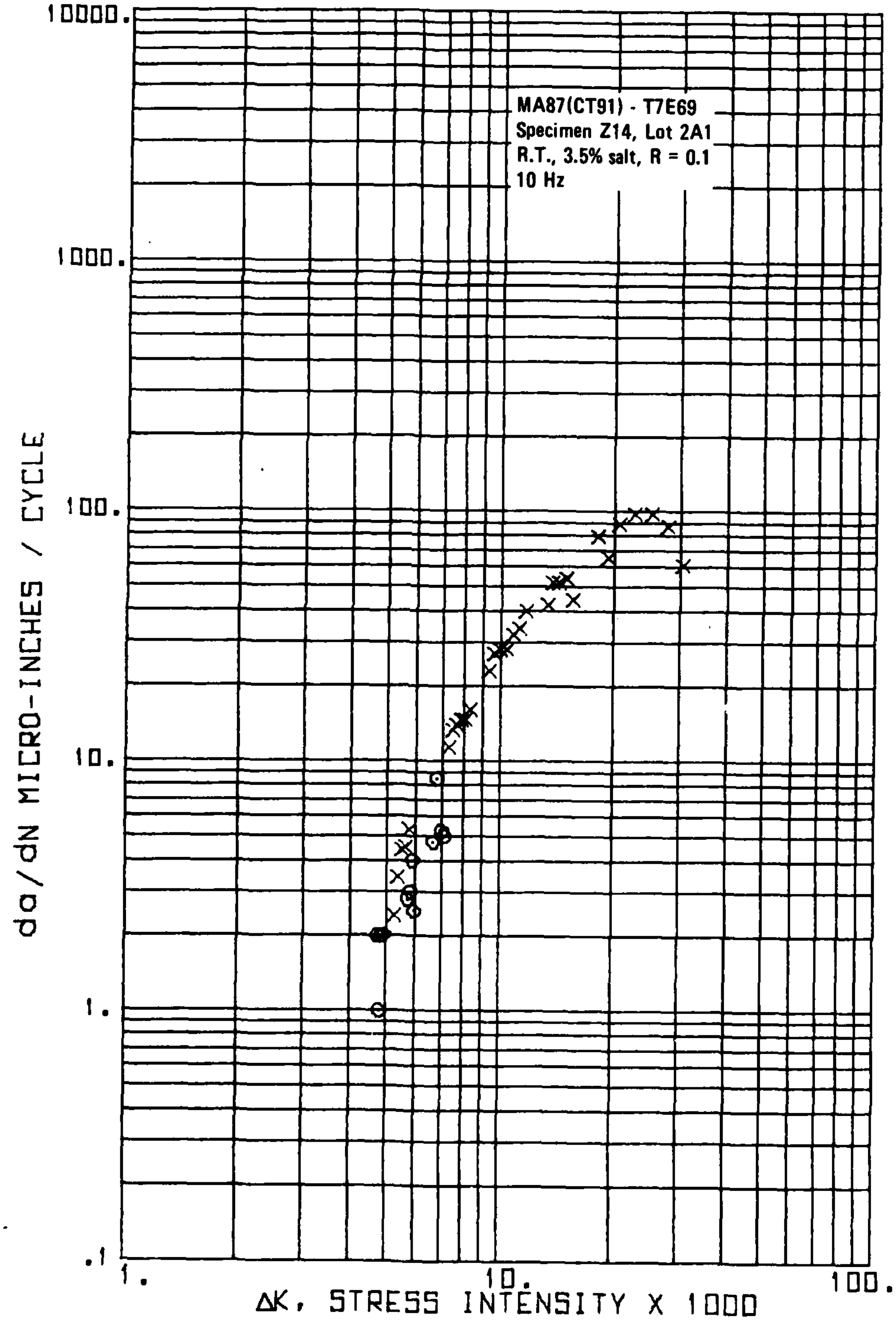


Figure 56. - Fatigue crack growth of specimen Z14, lot 2A1 in 3.5 percent salt solution.

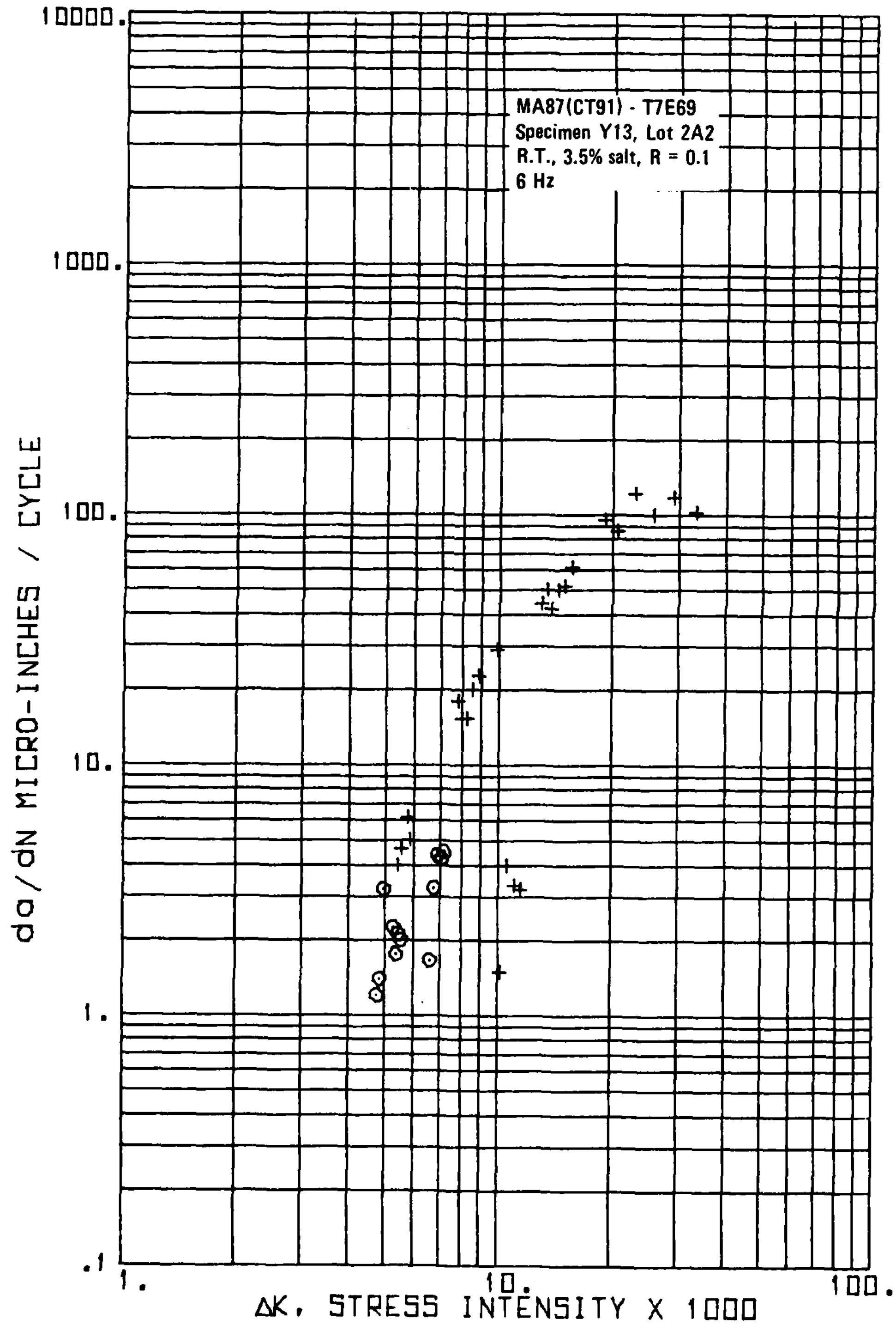


Figure 57. - Fatigue crack growth of specimen Y13, lot 2A2 in 3.5 percent salt solution.

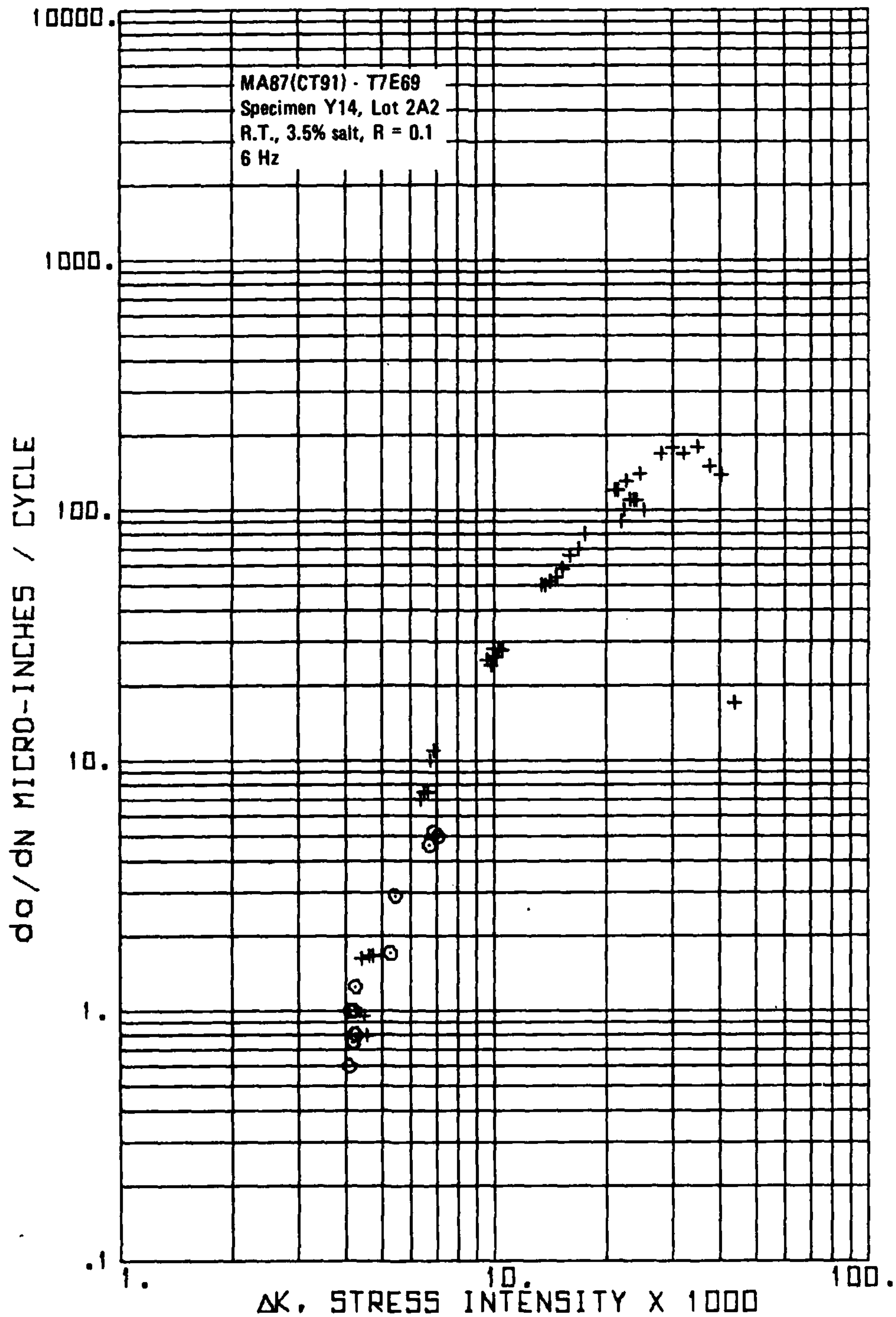


Figure 58. - Fatigue crack growth of specimen Y14, lot 2A2, in 3.5 percent salt solution.

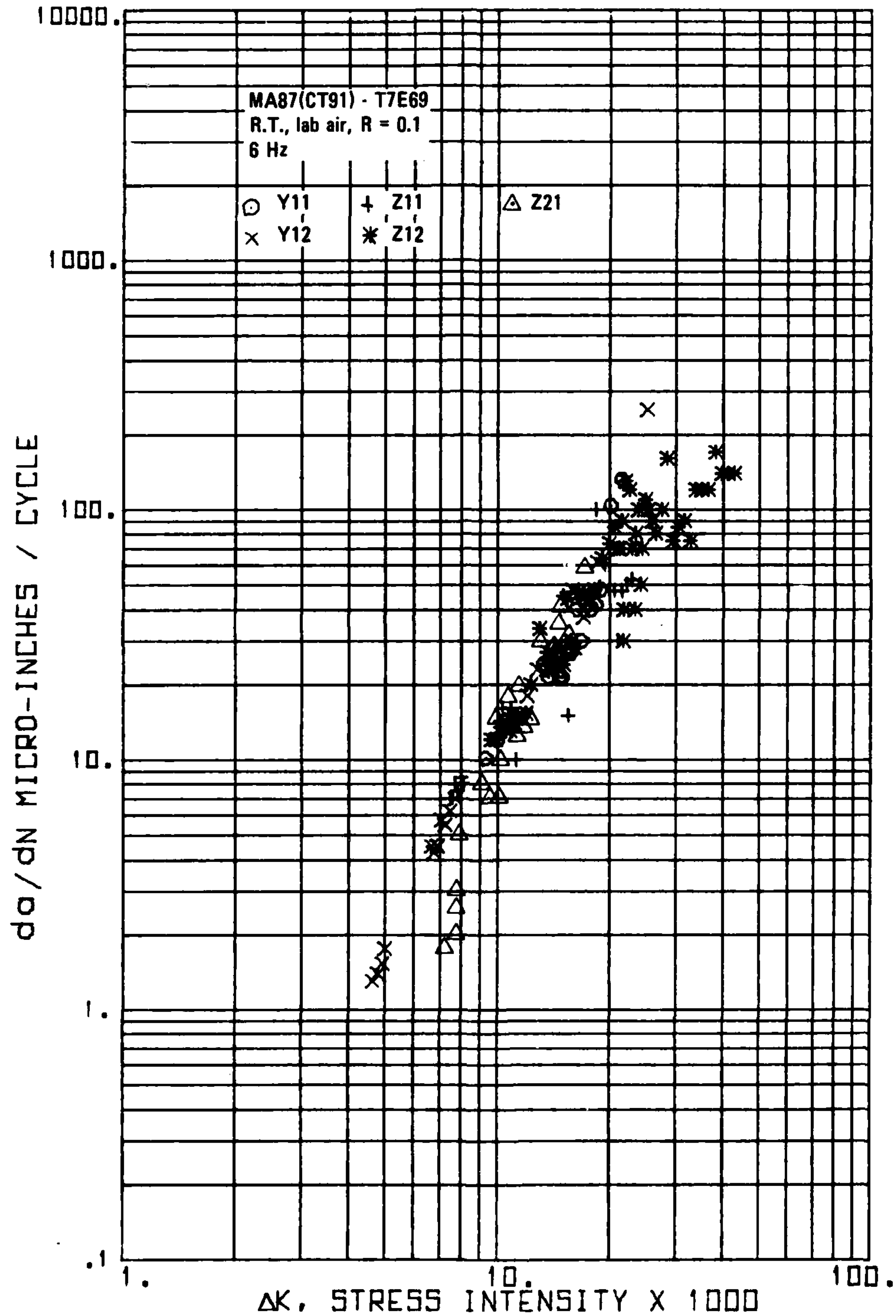


Figure 59. - Fatigue crack growth summary for lab air tests.

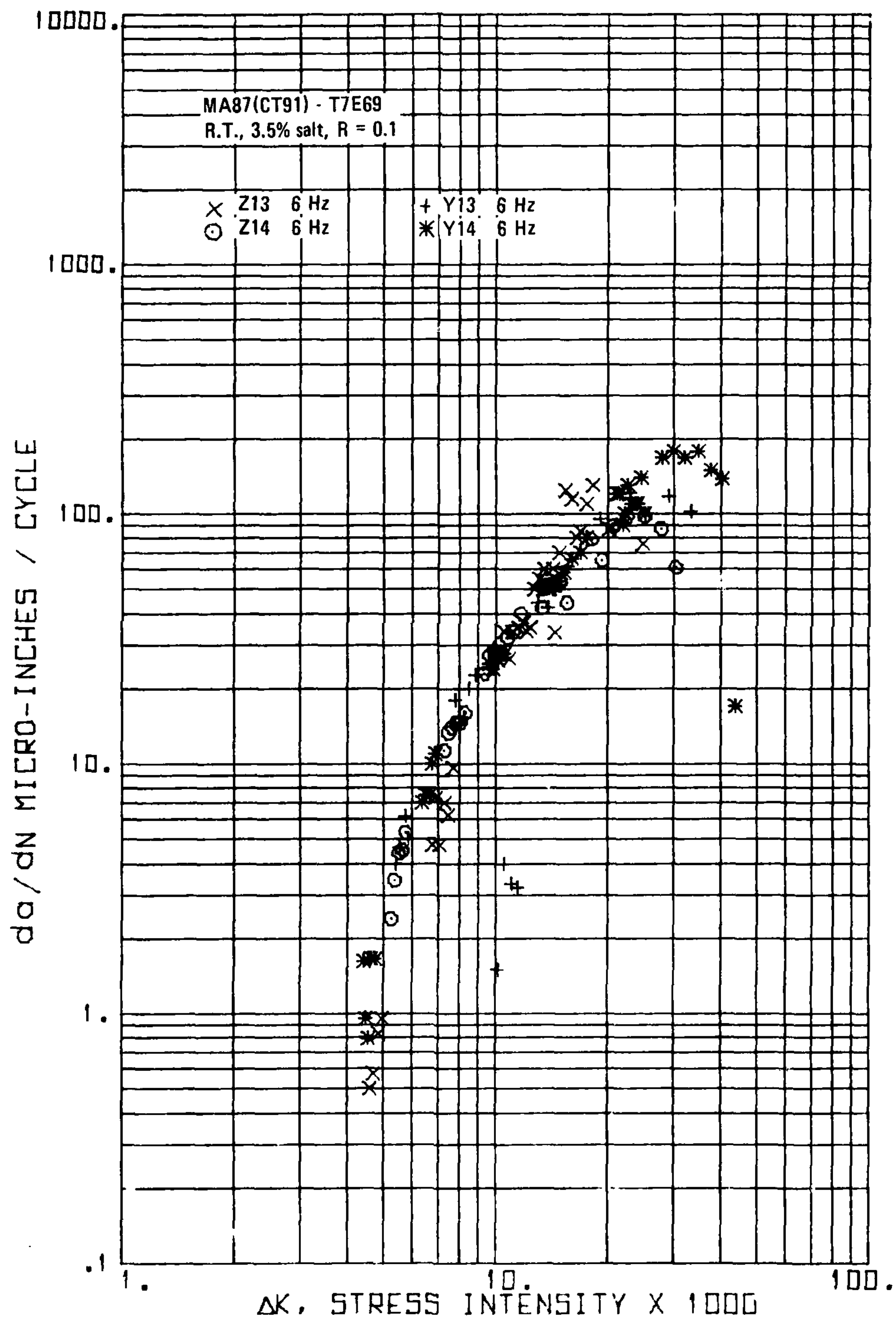


Figure 60. - Fatigue crack growth summary for 3.5 percent salt solution tests.

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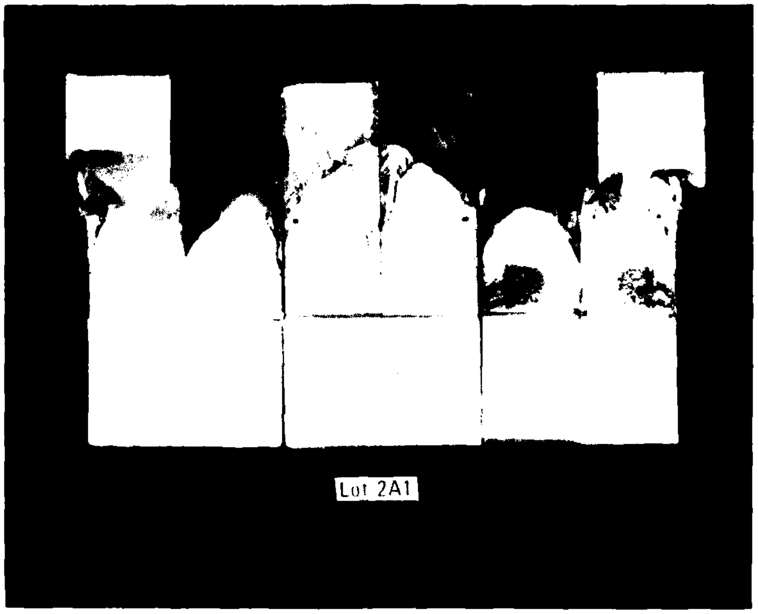
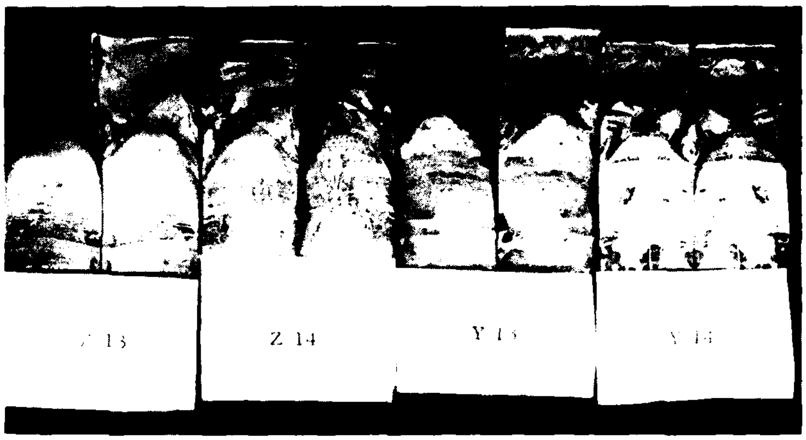


Lot 2A2

Figure 61. - Fatigue crack growth specimen fracture surfaces, tested in lab air.



Lot 2A1 Lot 2A2

Figure 62. - Fatigue crack growth specimen fracture surfaces, tested in 3.5 percent salt solution.

Constant Parameters:

$B = 0.750"$ $\sigma_{ys} = 80$ ksi

$W = 1.500"$

Defined Variables:

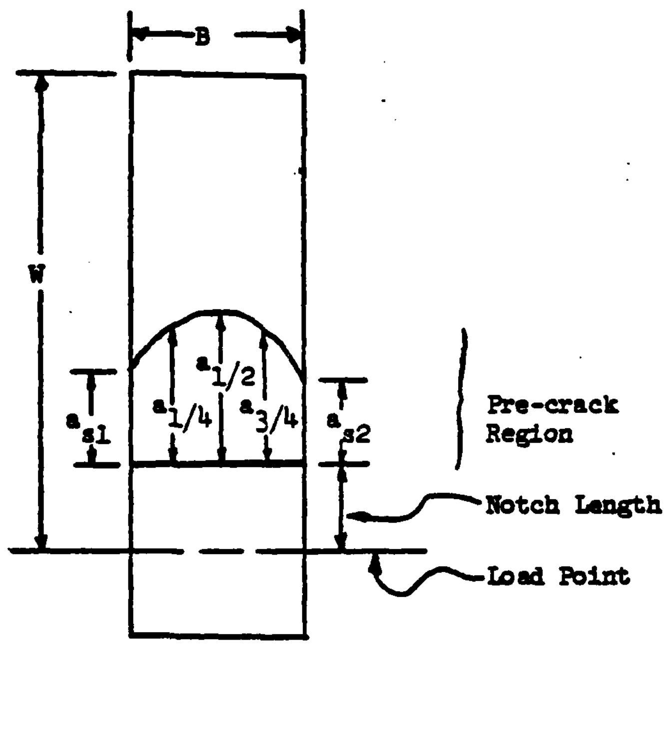
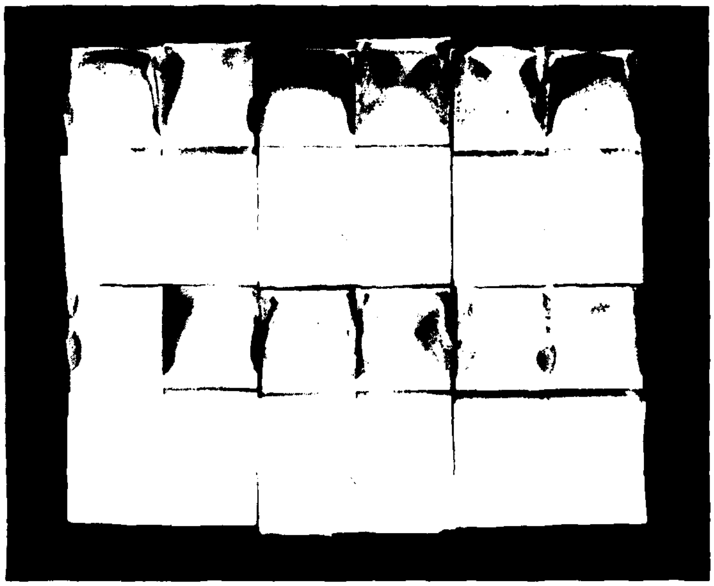


Figure 63. - Crack length measurement definitions for the compact tension specimens.



Lot 2A1

Lot 2A2

Figure 64. - Fracture toughness specimen fracture surfaces.

CONCLUSIONS

- The mechanical properties of MA87(CT91)-T7E69 production extrusions were uniform between the lots. The properties were also equal to or greater than the typical properties for 7075-T6 extrusions. The tensile, compression, shear, and bearing properties exceed the MIL-HDBK-5 "A" values for 7075-T6 extrusions.

- The MA87(CT91)-T7E69 extrusions were resistant to exfoliation when exposed to EXCO, salt spray or sea coast environments. No evidence of stress corrosion cracking was observed when specimens were stressed to 45 ksi in the alternate immersion corrosion test environment. However, pitting was observed on all corrosion specimens and did cause early faiures in stress corrosion tests. MA87(CT91) provides a significant corrosion resistant improvement over 7075-T6 extrusions, which are susceptible to exfoliation and to stress corrosion cracking at 7 ksi in the short transverse grain direction.

- The constant amplitude and spectrum fatigue performance of MA87(CT91)-T7E69 exceeded the design curves and typical fatigue data for 7075-T6 extrusions. The spectrum fatigue performance of MA87(CT91)-T7E69 extrusions also exceeded 7050-T7E73 extrusion performance.

- The fatigue crack growth and fracture toughness of MA87(CT91)-T7E69 extrusions were comparable to available data on 7075-T6 and T76 extrusions.

- The MA87(CT91)-T7E69 extrusions had a uniform fine grain structure free of voids and extraneous particles.

RECOMMENDATIONS

- The combination of properties obtained for MA87(CT91)-T7E69 extrusions make the material attractive for potential aircraft structural use; therefore, the evaluation of the material should be continued to accelerate the transition from developmental to standard production status.
- Corrosion protection systems to prevent pitting in MA87(CT91) should be evaluated.
- The data base for MA87(CT91) extrusions should be expanded to develop sufficient data to establish preliminary design allowables for a range of cross section sizes and thicknesses.
- The MA87(CT91) extrusions should be evaluated for their response to fabrication practices and the effect on properties.

REFERENCES

1. Brodie, Roy W. and Bakow, Leon, "Comparison of Engineering Properties of 7050-T7E73 and 7075-T6510 Extrusions for Potential P-3 Applications," NADC-76269-30 (LR28499) Lockheed-California Company, February 1978.

2. Rhodes, J. E. et al, "P-3A Service Life Extension Program (SLEP) Part 1 Volume 2," LR 27982-2, Lockheed-California Company, January 1977.

3. Van Orden, J. M. and Ryder, J. J., "Effect of Purity on Fatigue and Fracture of 7XXX-T76511 Aluminum Extrusion," LR28612, Lockheed-California Company, May 1978.